Spin Dependence in Polarized $p{\uparrow}\,p{\uparrow} \rightarrow pp$ & $p{\uparrow}C \rightarrow pC$ Elastic Scattering in the CNI Region
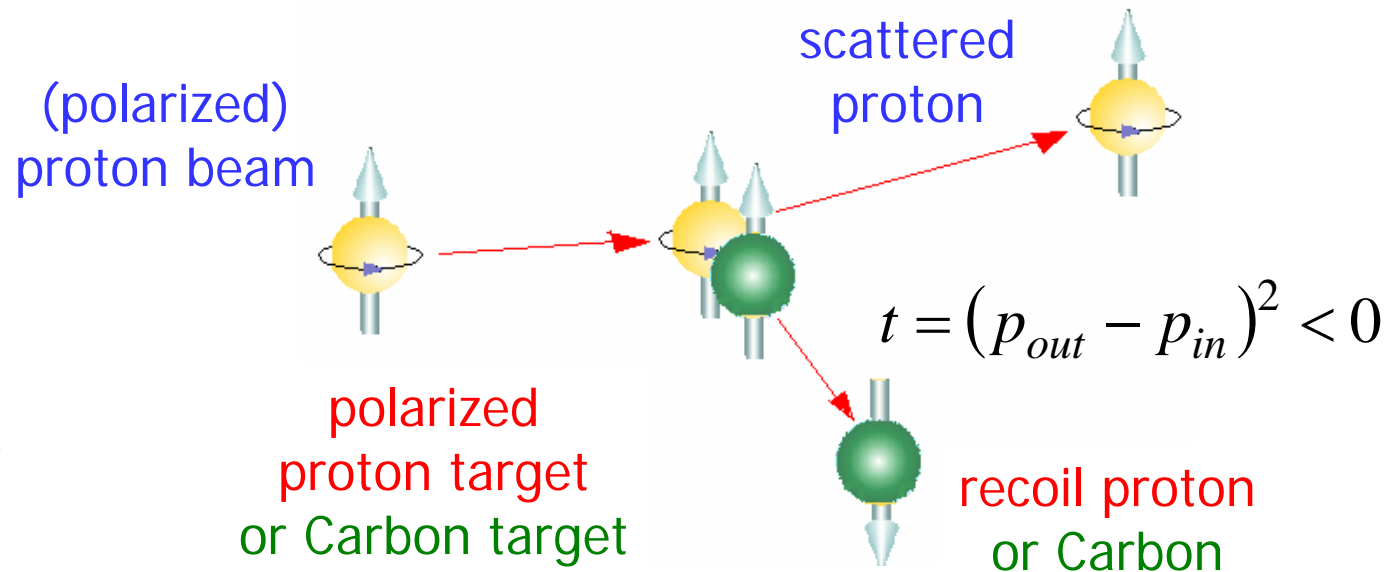
A. Bravar, I. Alekseev, G. Bunce, S. Dhawan, R. Gill,

H. Huang, W. Haeberli, G. Igo, O. Jinnouchi, A. Khodinov, K. Kurita,

Y. Makdisi, A. Nass, H. Okada, N. Saito, H. Spinka, E. Stephenson,

D. Svirida, C. Whitten, T. Wise, J. Wood, A. Zelenski

XVIIth Rencontres de Blois
Chateau de Blois
May 19, 2005

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

The Elastic Process: Kinematics

(polarized)
proton beam

scattered
proton

$$t = \left(p_{out} - p_{in}\right)^2 < 0$$

RHIC beams +
internal targets $\equiv$
fixed target mode
$\sqrt{s} \sim 14 \text{ GeV}$

polarized
proton target
or Carbon target

recoil proton
or Carbon

essentially 1 free parameter:
   momentum transfer $t = (p_3 - p_1)^2 = (p_4 - p_2)^2 < 0$
   + center of mass energy $s = (p_1 + p_2)^2 = (p_3 - p_4)^2$
   + azimuthal angle φ if polarized !

$\Rightarrow$ elastic pp kinematics fully constrained by recoil proton only !

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

Helicity Amplitudes for spin ½ ½ → ½ ½

Scattering process described in terms of Helicity Amplitudes ϕ_i
All dynamics contained in the Scattering Matrix M
(Spin) Cross Sections expressed in terms of

observables:

3 ×-sections

5 spin asymmetries

$$\text{spin non–flip} \quad \phi_1(s,t) = \langle + + | M | + + \rangle$$

$$\text{double spin flip} \quad \phi_2(s,t) = \langle + + | M | - - \rangle$$

$$\text{spin non–flip} \quad \phi_3(s,t) = \langle + - | M | + - \rangle$$

$$\text{double spin flip} \quad \phi_4(s,t) = \langle + - | M | - + \rangle$$

$$\text{single spin flip} \quad \phi_5(s,t) = \langle + + | M | + - \rangle = -\langle + + | M | - + \rangle$$

$? \quad \langle \mathbf{M} \rangle$

identical spin ½ particles
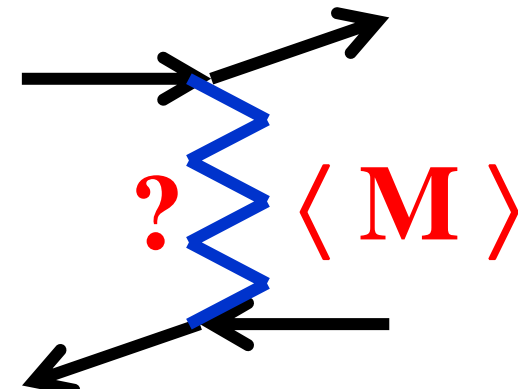
$$A_N = \frac{\sigma^{\Uparrow} - \sigma^{\Downarrow}}{\sigma^{\Uparrow} + \sigma^{\Downarrow}}$$

$$A_N(s,t)\frac{d\sigma}{dt} = \frac{-4\pi}{s^2}\text{Im}\left\{ \phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4) \right\}$$

$$A_{NN} = \frac{\sigma^{\uparrow\uparrow+\downarrow\downarrow} - \sigma^{\uparrow\downarrow+\downarrow\uparrow}}{\sigma^{\uparrow\uparrow+\downarrow\downarrow} + \sigma^{\uparrow\downarrow+\downarrow\uparrow}}$$

$$A_{NN}(s,t)\frac{d\sigma}{dt} = \frac{4\pi}{s^2}\left\{ 2|\phi_5|^2 + \text{Re}\left(\phi_1^*\phi_2 - \phi_3^*\phi_4\right) \right\}$$

formalism well developed, however not much data !
only A_N studied / measured to some extent

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

The Very Low t Region

around $t \sim -10^{-3}$ (GeV/c)^2 A$_{\text{hadronic}} \approx$ A$_{\text{Coulomb}}$

$\Rightarrow$ INTERFERENCE
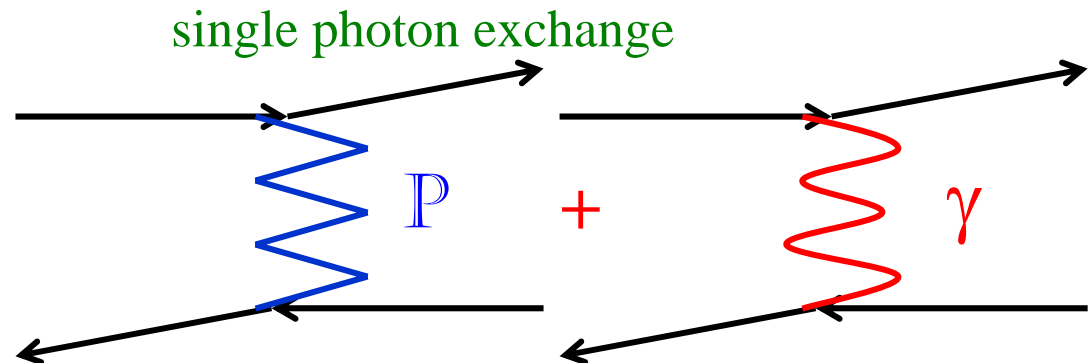
CNI = Coulomb – Nuclear Interference

scattering amplitudes modified to include also electromagnetic contribution

$$\phi_i^{had} \rightarrow \phi_i^{had} + \phi_i^{em} e^{i\delta}$$

hadronic interaction described in terms of Pomeron (Reggeon) exchange

electromagnetic   single photon exchange

$\sigma = |$A$_{\text{hadronic}} +$ A$_{\text{Coulomb}}|^2$ $\mathbb{P}$ $+$ γ

unpolarized $\Rightarrow$ clearly visible in the cross section dσ/dt   **charge**

polarized $\Rightarrow$ "left – right" asymmetry A$_N$ **magnetic moment**

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

A_N & Coulomb Nuclear Interference

the left – right scattering asymmetry A_N arises from the interference of the spin non-flip amplitude with the spin flip amplitude (Schwinger)

$$A_N = C_1 \phi_{flip}^{em}{}^* \phi_{non-flip}^{had} + C_2 \phi_{flip}^{had}{}^* \phi_{non-flip}^{had}$$

$$\propto (\mu-1)_p \qquad \propto \sigma^{pp}{}_{had}$$

in absence of hadronic spin – flip contributions A_N is exactly calculable (Kopeliovich & Lapidus):

$$A_N = \sqrt{\frac{8\pi Z\alpha}{m_p^2 \sigma_{tot}^{pA}}} \frac{y^{3/2}}{1+y^2}(\mu-1) \qquad y = \frac{\sigma_{tot}^{pA} t}{8\pi Z\alpha}$$

hadronic spin- flip modifies the QED "predictions"

$$\frac{\mu_p-1}{2} \rightarrow \frac{\mu_p-1}{2} - I_5 + \frac{\mu_p-1}{2}I_2$$

interpreted in terms of Pomeron spin – flip and parametrized as

$$\phi_5^{had} = \tau(s)\frac{\sqrt{-t}}{m_p}\phi_1^{had}$$

$A_N(t)$

Analyzing power

p+C–>p+C
p+p–>p+p

−t [GeV**2]

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY
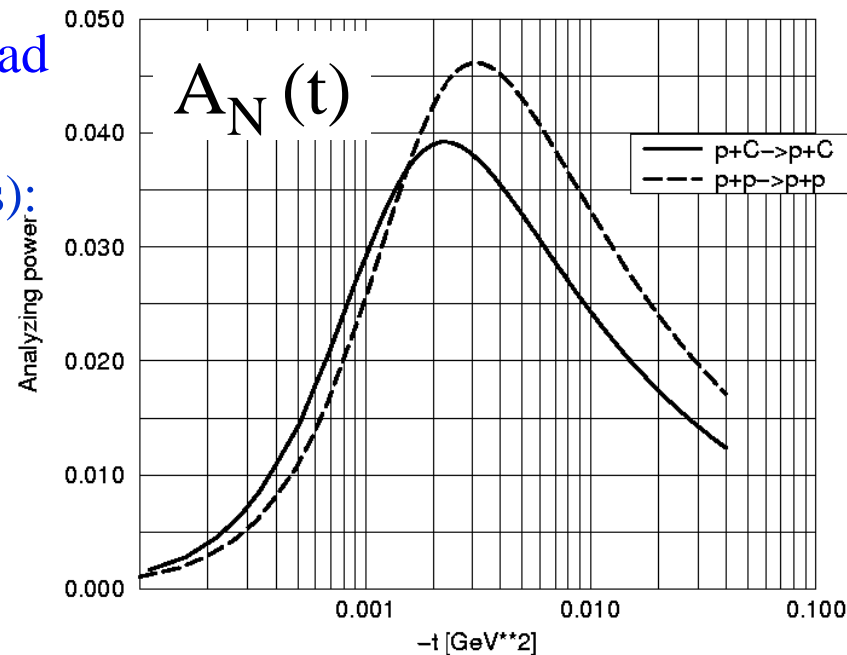
On the Polarization of Fast Neutrons

JULIAN SCHWINGER

Harvard University, Cambridge, Massachusetts

(Received January 8, 1948)

ALTHOUGH the production of polarized thermal neutrons has long been an accomplished fact, no such success has been forthcoming with fast neutrons. Only one method for the polarization of fast neutrons has thus far been suggested,[1] of which the essential mechanism is the large, effective nuclear spin-orbit interaction present when neutrons are resonance scattered by helium and similar nuclei. It is the purpose of this note to suggest a second mechanism for polarizing fast neutrons—the spin-orbit interaction arising from the motion of the neutron magnetic moment in the nuclear Coulomb field. Despite the apparent small magnitude of this interaction, the long-range nature of the Coulomb field is such that the use of small scattering angles will produce almost complete polarization under ideal conditions. A closely related phenomenon produced by this electromagnetic interaction is an additional scattering of unpolarized neutrons which increases rapidly with decreasing

where $k=p/\hbar$ is the neutron wave number. Hence, the unscreened Coulomb field of a point nucleus will be effective for scattering in the angular range:

$$1/ka \ll 2 \sin\vartheta/2 \ll 1/kR. \qquad (3)$$

If the nuclear radius and atomic screening radius are taken to be

$$R = 1.5 \cdot 10^{-13} A^{\frac{1}{3}} \text{ cm} \quad \text{and} \quad a = 0.53 \cdot 10^{-8} Z^{-\frac{1}{3}} \text{ cm},$$
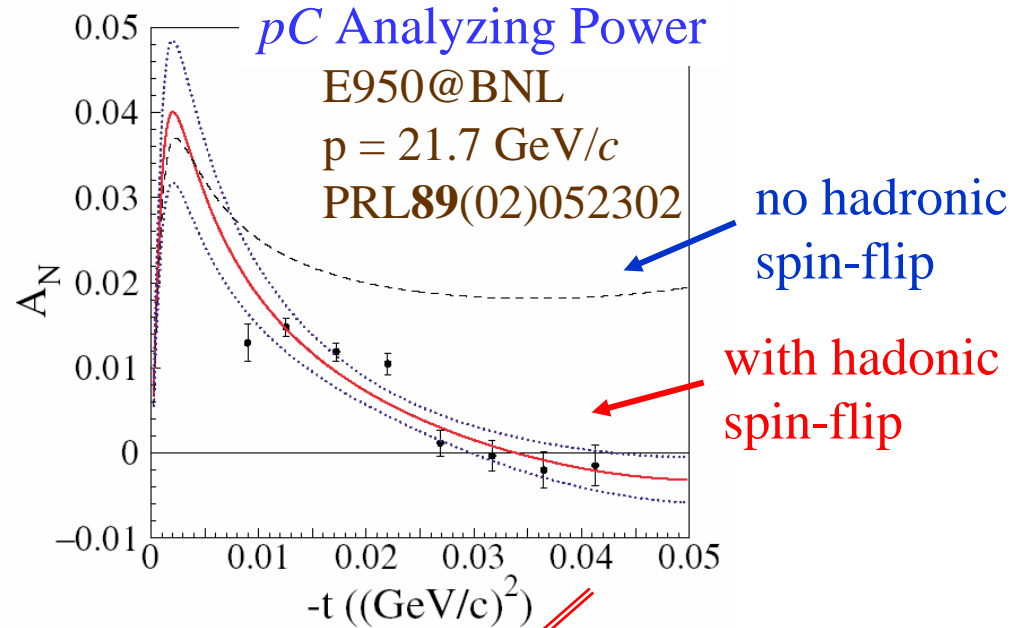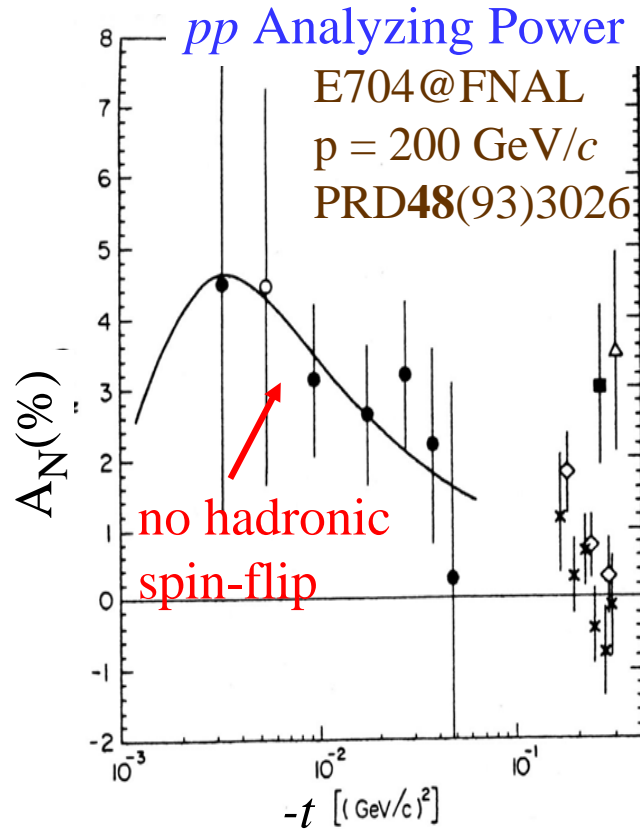
the angle restrictions for a 1-Mev neutron scattered in Pb, for example, are

$$4 \cdot 10^{-4} \ll 2 \sin\vartheta/2 \ll \tfrac{1}{2}. \qquad (4)$$

The electromagnetic scattering of a neutron under these conditions can be calculated with the plane wave Born approximation, for the nuclear scattered wave is negligible compared with the incident wave at the significant scattering distances. We denote the incident plane wave by

Some A_N measurements in the CNI region

pp Analyzing Power

E704@FNAL
p = 200 GeV/c
PRD**48**(93)3026

no hadronic
spin-flip

pC Analyzing Power

E950@BNL
p = 21.7 GeV/c
PRL**89**(02)052302

no hadronic
spin-flip

with hadonic
spin-flip

$r_5{}^{pC} \propto F_s{}^{had} / Im\ F_0{}^{had}$

Re r_5 = 0.088 ± 0.058

Im r_5 = −0.161 ± 0.226

highly anti-correlated

Alessandro Bravar

NATIONAL LABORATORY
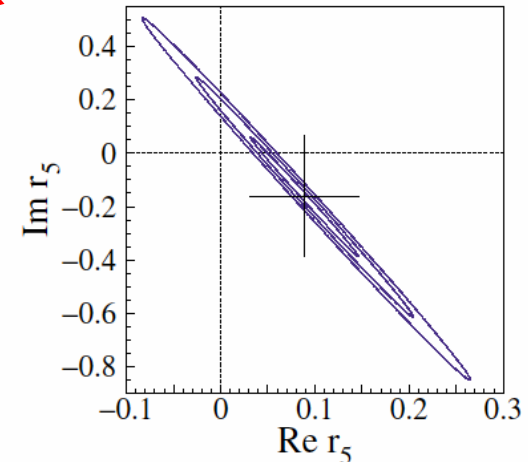
RHIC *pp* accelerator complex

Alessandro Bravar
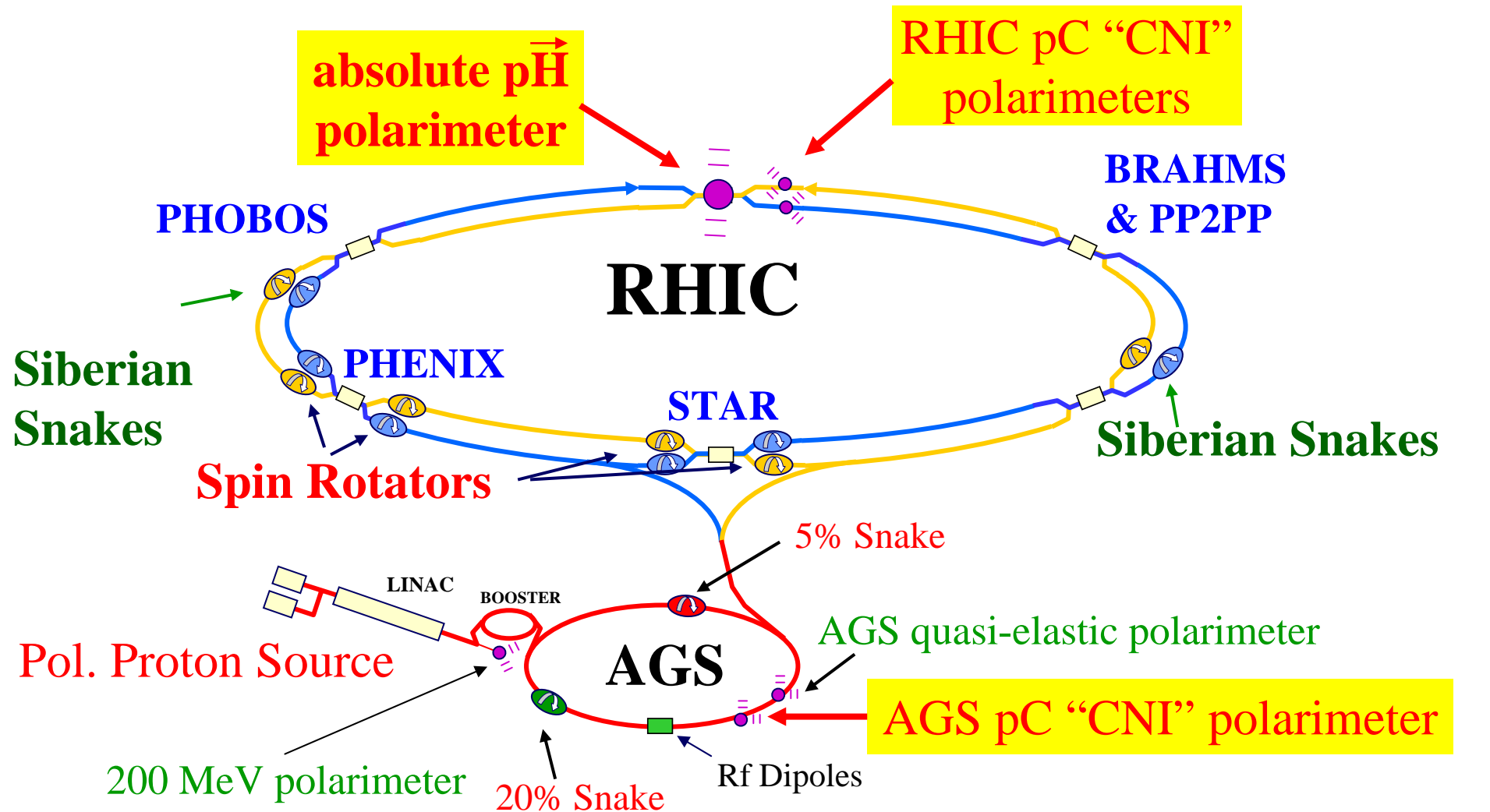
Polarimetry : Impact on RHIC Spin Physics

Single Spin Asymmetries

Versus
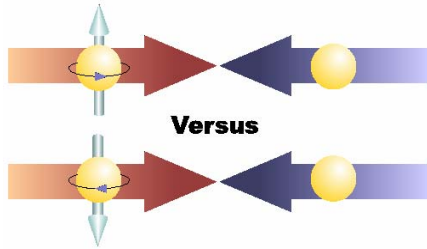
Physics Asymmetries

$$A_N = \frac{1}{P_B}\left(\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right)$$

$$P_B = -\frac{1}{A_N} \cdot \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

recoil

Double Spin Asymmetries

Versus
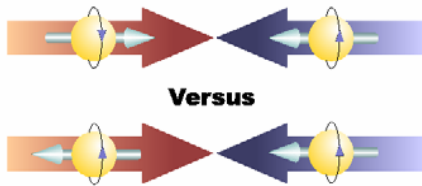
$$A_{LL} = \frac{1}{P_B{}^2}\left(\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}\right) \Rightarrow \boxed{\Delta G}$$
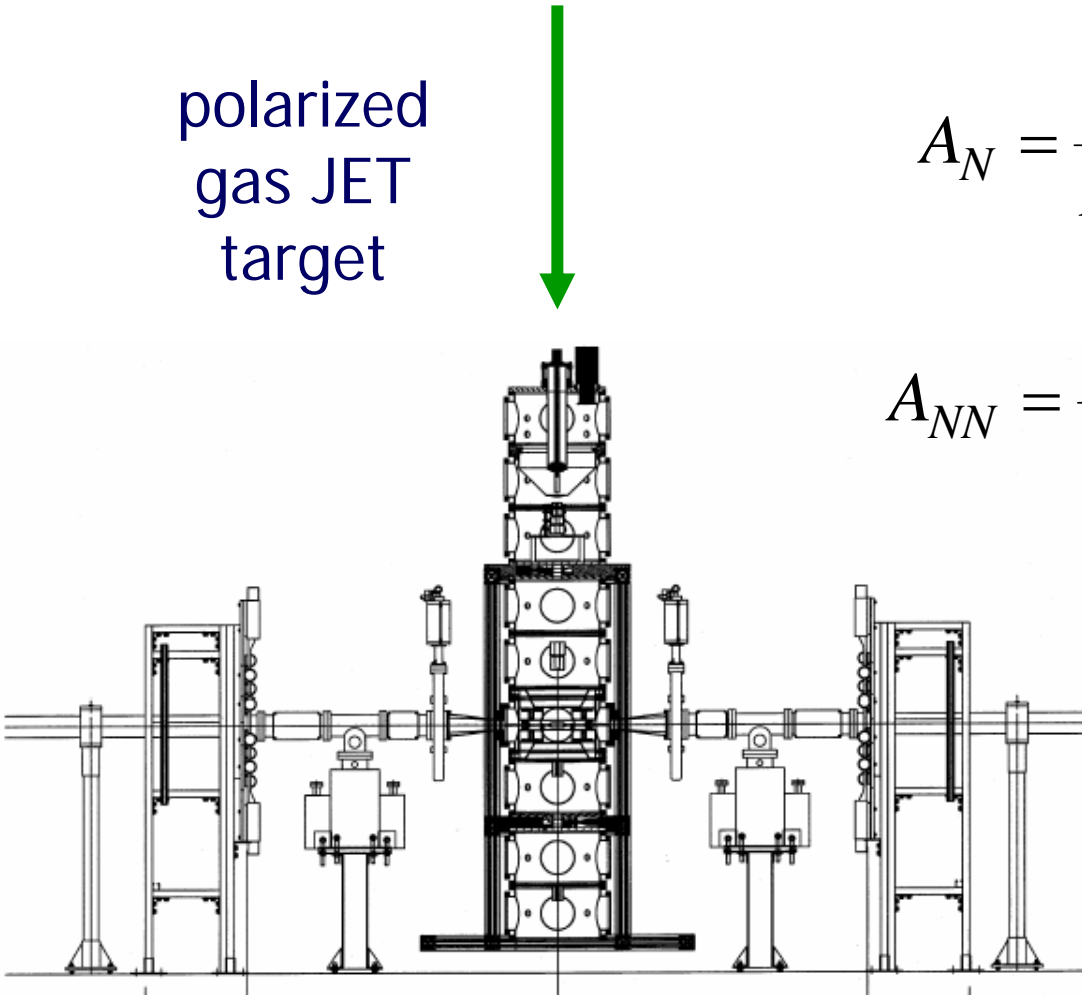
measurements

- measured spin asymmetries normalized by P_B to extract Physics Spin Observables
- RHIC Spin Program requires $\Delta P_{beam} / P_{beam} \sim 0.05$
- normalization $\Rightarrow$ scale uncertainty
- polarimetric process with large σ and known A_N
  - pC elastic scattering in CNI region, $A_N \sim 1 - 2\ \%$
  - fast measurements
  - requires absolute calibration $\rightarrow$ polarized gas jet target

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

$p \uparrow p \rightarrow pp$ and $p \uparrow p \uparrow \rightarrow pp$ with a Polarized Gas Jet Target

polarized gas JET target

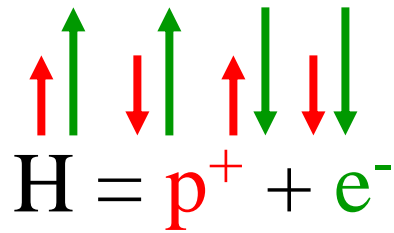$$A_N = \frac{1}{P_T} \frac{\left(N_L^{\Uparrow} + N_R^{\Downarrow}\right) - \left(N_R^{\Uparrow} + N_L^{\Downarrow}\right)}{\left(N_L^{\Uparrow} + N_R^{\Downarrow}\right) + \left(N_R^{\Uparrow} + N_L^{\Downarrow}\right)}$$

$$A_{NN} = \frac{1}{P_T P_B} \frac{N^{\uparrow\uparrow+\downarrow\downarrow} - N^{\uparrow\downarrow+\downarrow\uparrow}}{N^{\uparrow\uparrow+\downarrow\downarrow} + N^{\uparrow\downarrow+\downarrow\uparrow}}$$
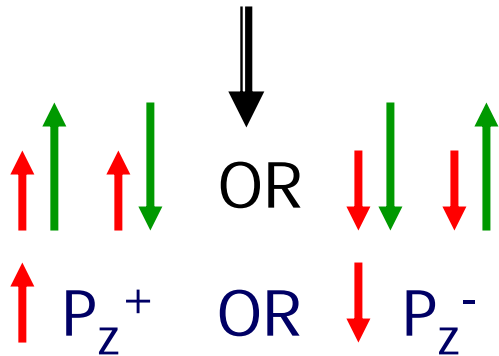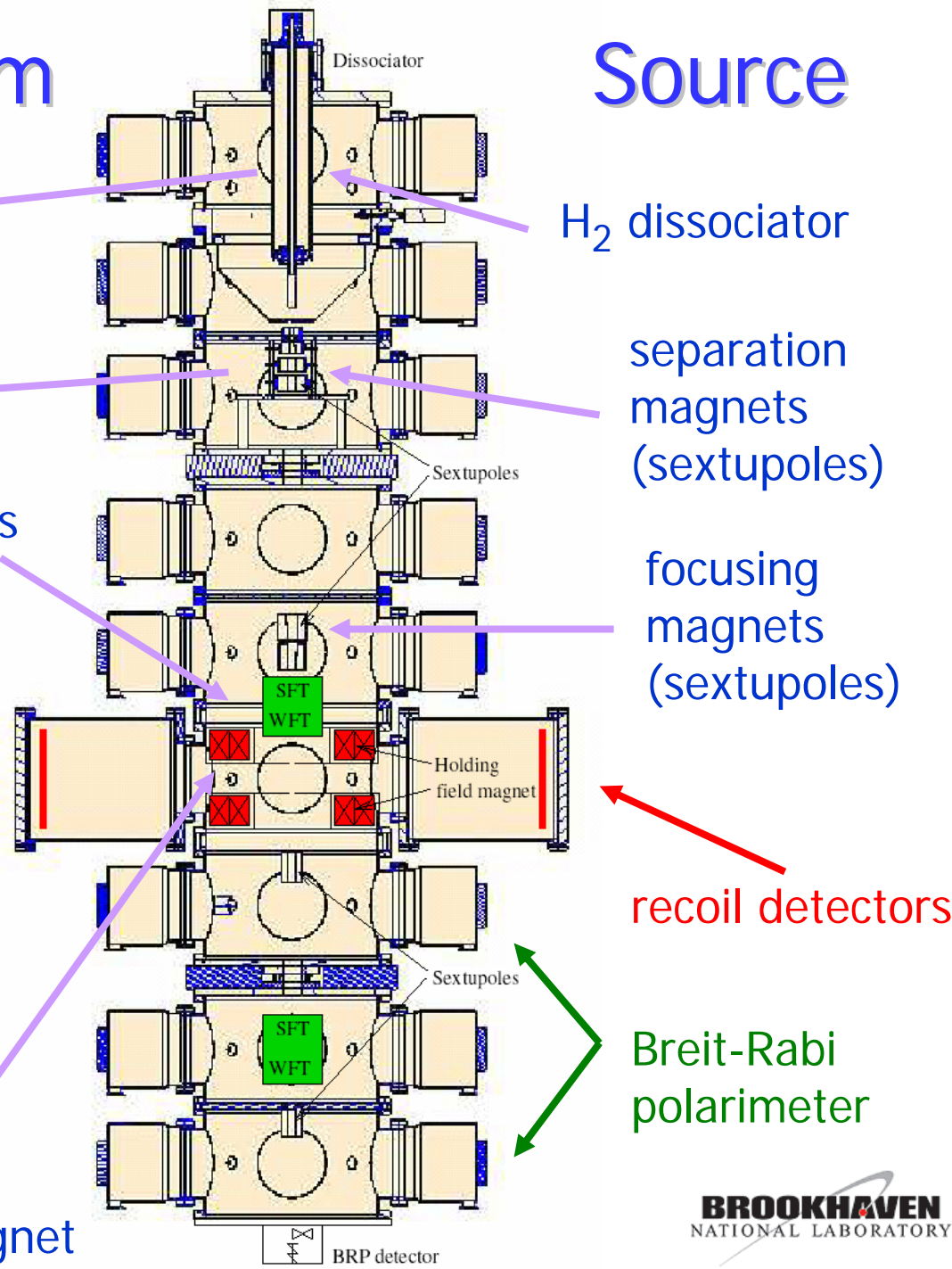
RHIC polarized proton beams

Alessandro Bravar

The Atomic H Beam   Source

$$H = p^+ + e^-$$

OR

$\uparrow P_z^+$ OR $\downarrow P_z^-$

record beam intensity
100% eff. RF transitions
focusing high intensity
B-R polarimeter

E D S 0 5

holding field magnet

Dissociator

H_2 dissociator

separation
magnets
(sextupoles)

Sextupoles

RF transitions

focusing
magnets
(sextupoles)

SFT
WFT

Holding
field magnet

recoil detectors

Sextupoles

SFT
WFT

Breit-Rabi
polarimeter

BRP detector

BROOKHAVEN
NATIONAL LABORATORY

JET target polarization & performance

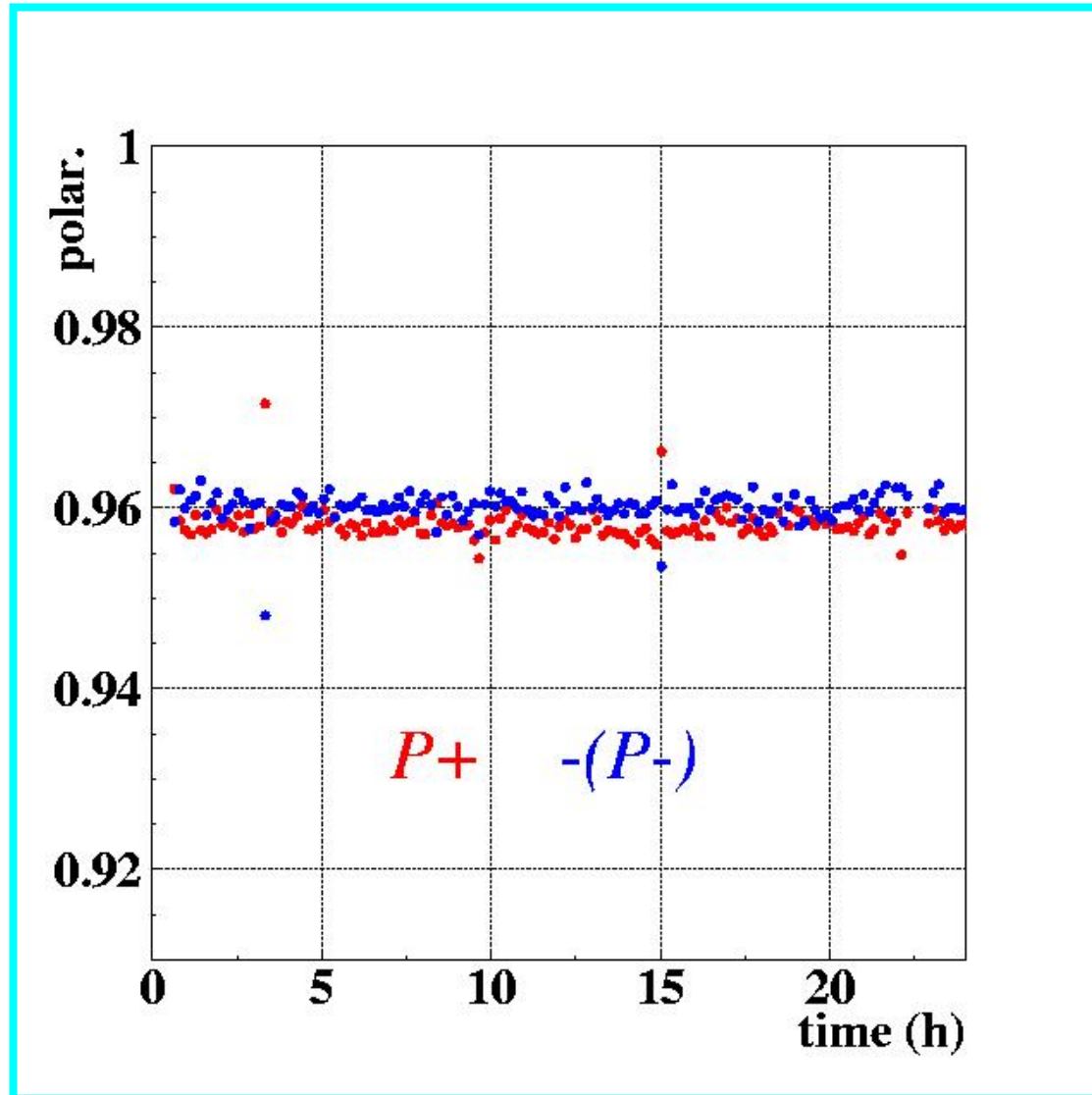the JET ran with an average intensity of 1×10^{17} atoms / sec

the JET thickness of 1×10^{12} atoms/cm^2 record intensity

target polarization cycle +/0/- ~ 500 / 50 / 500 sec

polarization to be scaled down due to a ~3% H_2 background:

P_{target} ~ 0.924 ± 0.018

(current understanding)

no depolarization from beam wake fields observed !

$P+$ $-(P-)$

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

The Polarized Jet Target under development

Electronics racks

Vac. gauges monitors

Turbo pump controllers
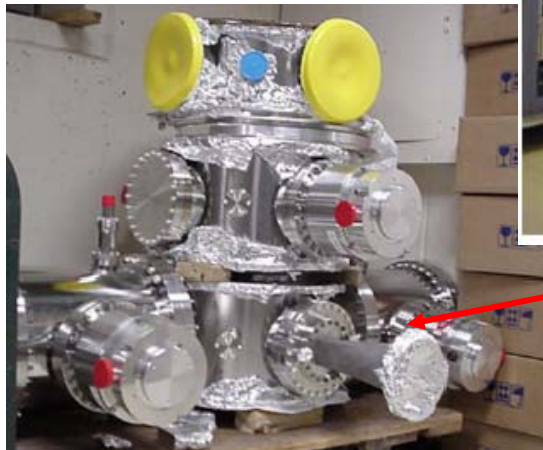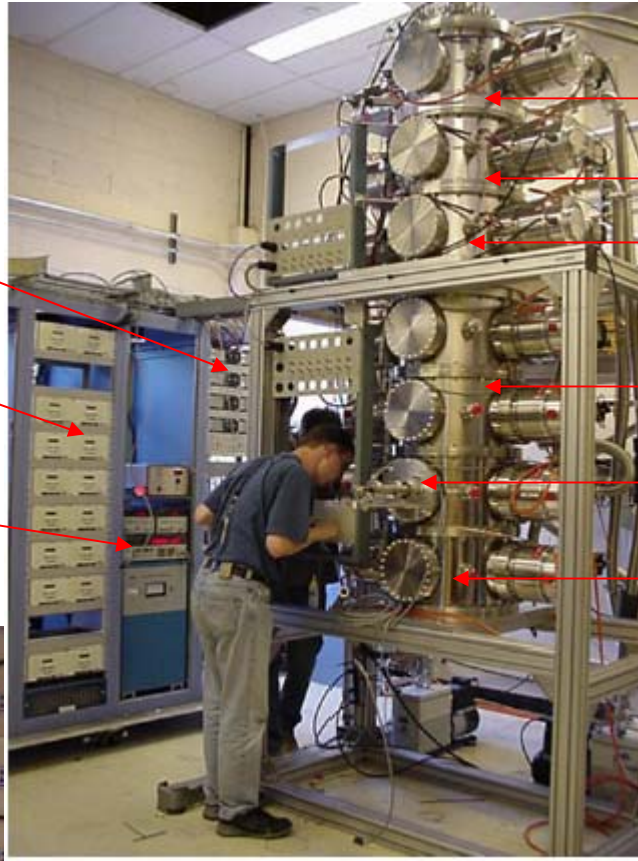
Dissociator RF systems

Dissociator stage

Baffle location
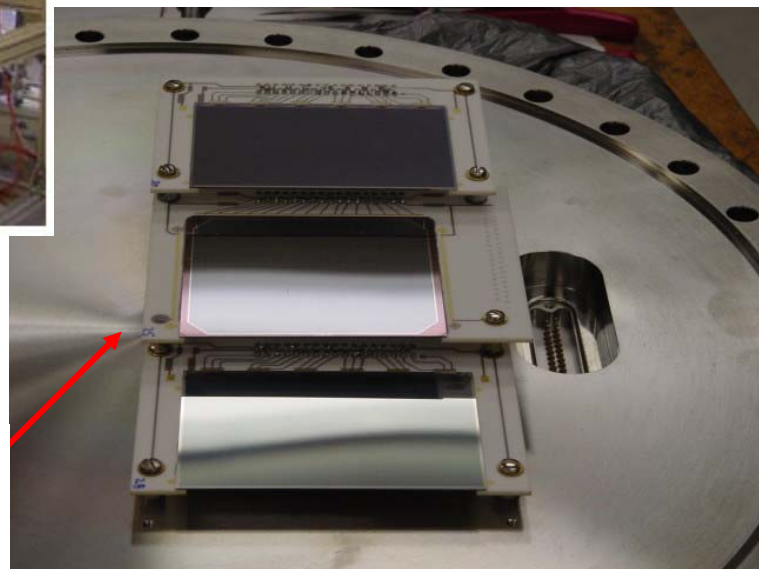
Sextupoles 1-4

Sextupoles 5-6

Profile measurement

BRP vacuum vessel

Target chamber &
beam pipe adapters

Recoil spectrometer
silicon detectors

E D S 0 5

Recoil Si spectrometer
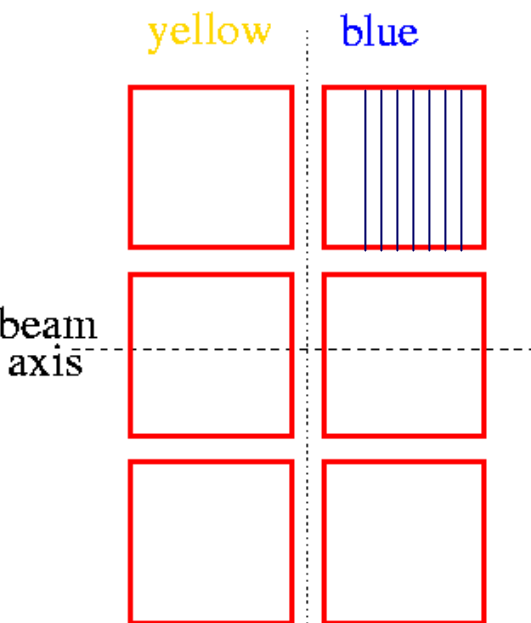
6 Si detectors covering
the blue beam =>
MEASURE
   energy   (res. < 50 keV)
   time of flight   (res. < 2 ns)
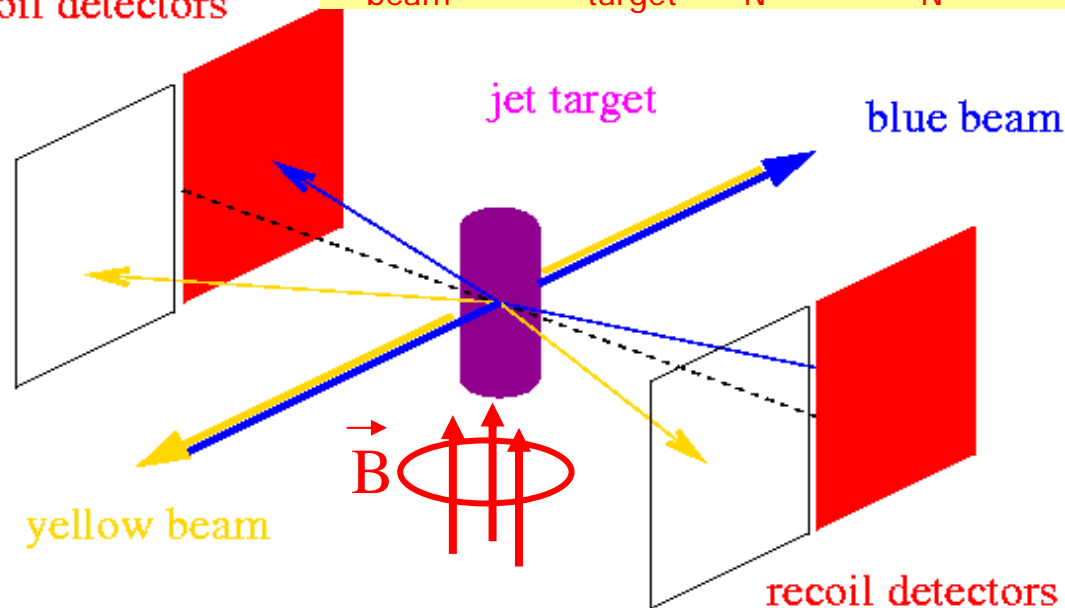   scattering angle (res. ~ 5 mrad)
of recoil protons from
$pp \rightarrow pp$ elastic scattering

recoil detectors

jet target

blue beam

$\vec{B}$

yellow beam

recoil detectors

yellow   blue

beam axis

72 x 64 mm^2

HAVE "design"
azimuthal coverage

one Si layer only
$\Rightarrow$ smaller energy range
$\Rightarrow$ reduced bkg rejection power

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

Jet-Target Holding Magnetic Field (1.0)

1.0 kGauss

$$\int B\,dl \sim 0$$

B_z (Gauss)

$+\quad-\quad+$

displacement (cm)

p = 30 MeV/c ($|t|\sim10^{-3}$)

p = 100 MeV/c ($|t|\sim10^{-2}$)

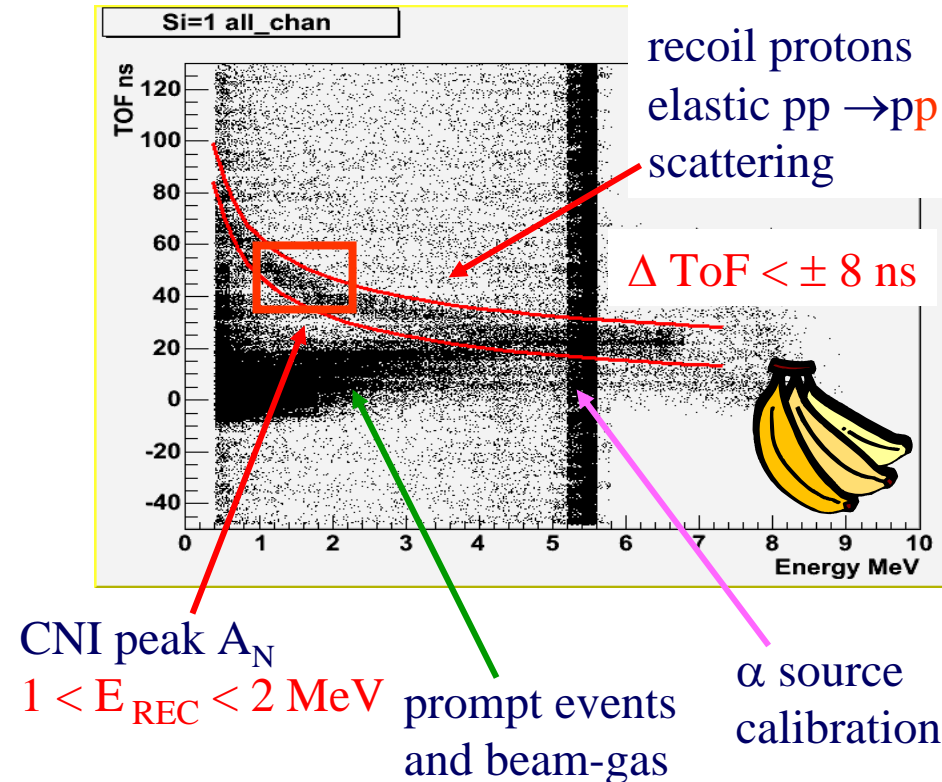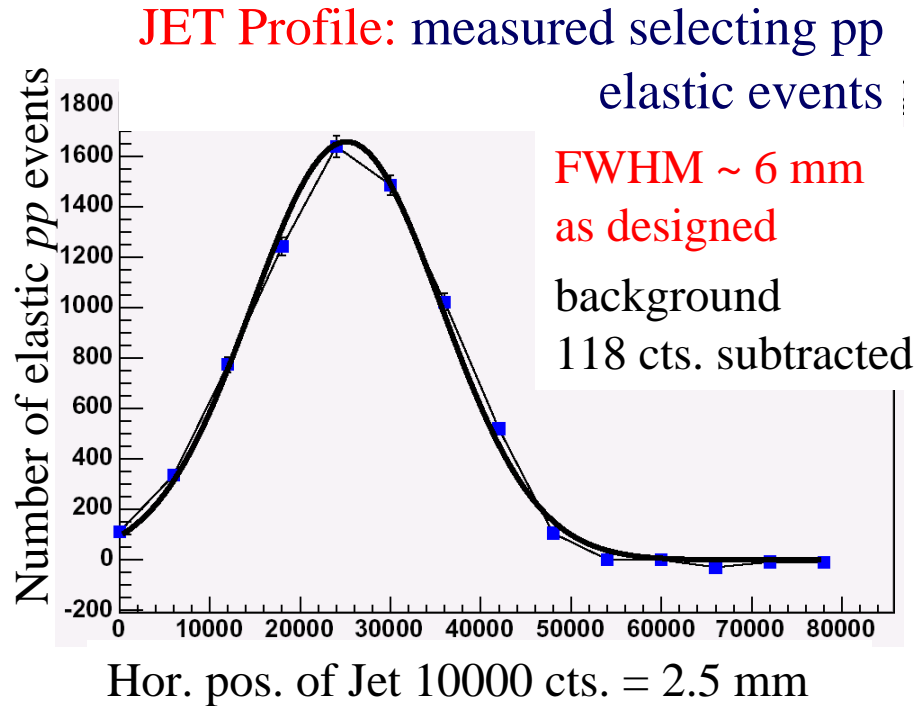Helmholtz coils
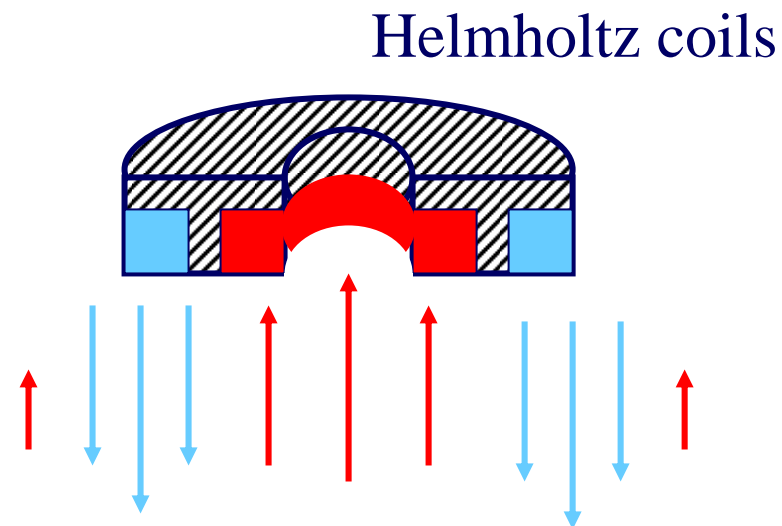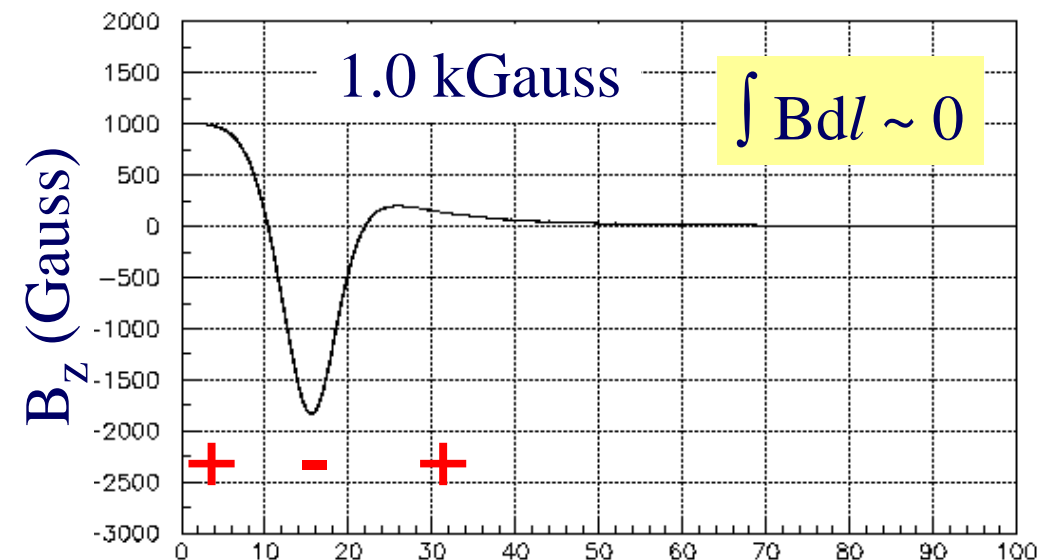
almost no effect on recoil proton trajectories:

left – right hit profiles & left – right acceptances almost equal
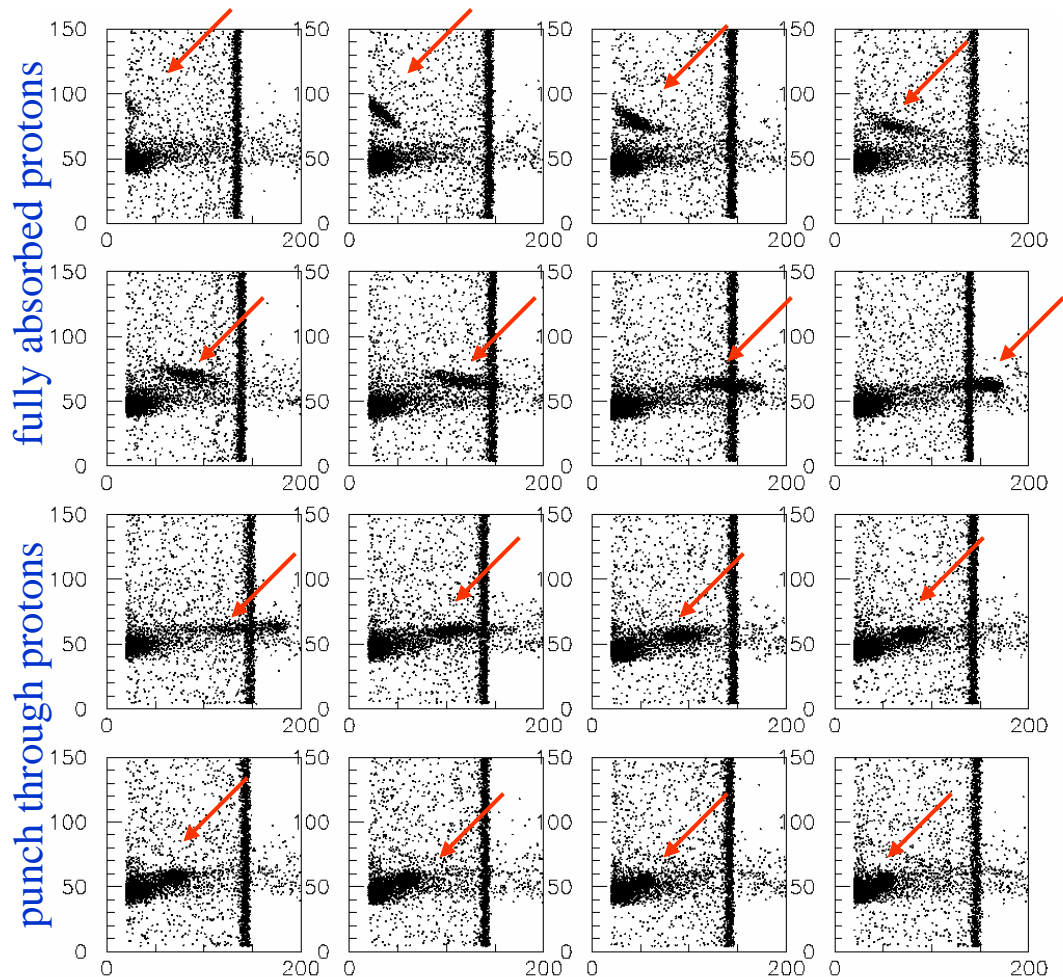(also under reversal of holding field)

EDS05

Alessandro Bravar
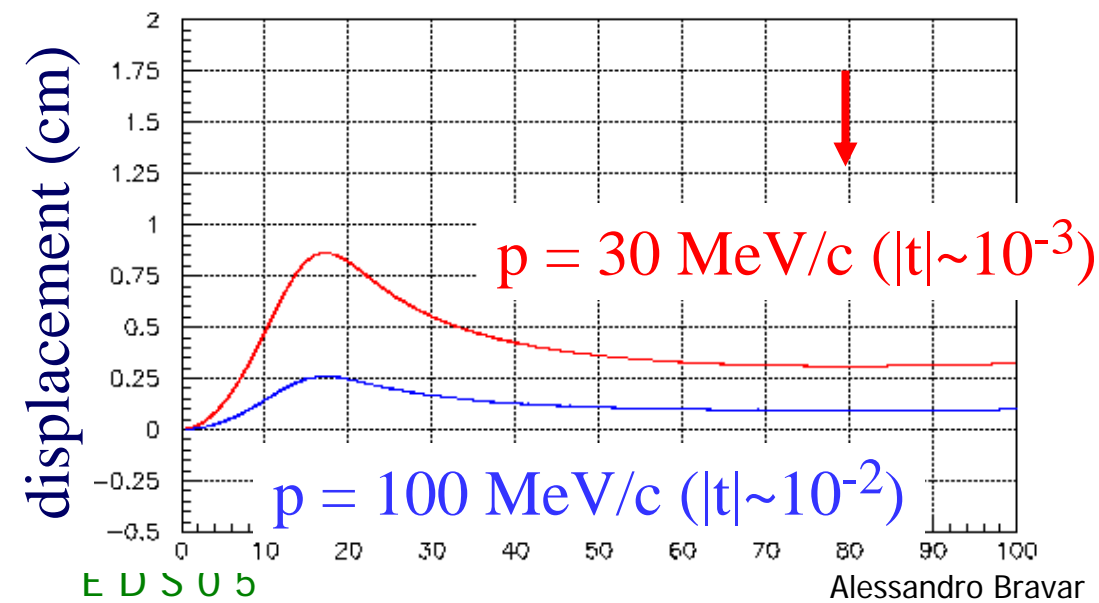
pp elastic data collected

ToF vs E_{REC} correlation
$T_{kin} = \frac{1}{2} M_R (dist/ToF)^2$

JET Profile: measured selecting pp
elastic events

FWHM ~ 6 mm
as designed

background
118 cts. subtracted

Hor. pos. of Jet 10000 cts. = 2.5 mm

Number of elastic *pp* events

Si=1 all_chan

recoil protons
elastic pp →pp
scattering

Δ ToF < ± 8 ns

CNI peak A_N
$1 < E_{REC} < 2$ MeV

prompt events
and beam-gas

α source
calibration

- recoil protons unambiguously identified !

- 100 GeV ~ 1.8×10^6 events for $1.5 \times 10^{-3} < -t < 1.0 \times 10^{-2}$ GeV^2
  similar statistics for $1.0 \times 10^{-2} < -t < 3.0 \times 10^{-2}$ GeV^2

- 24 GeV ~ 300 k events

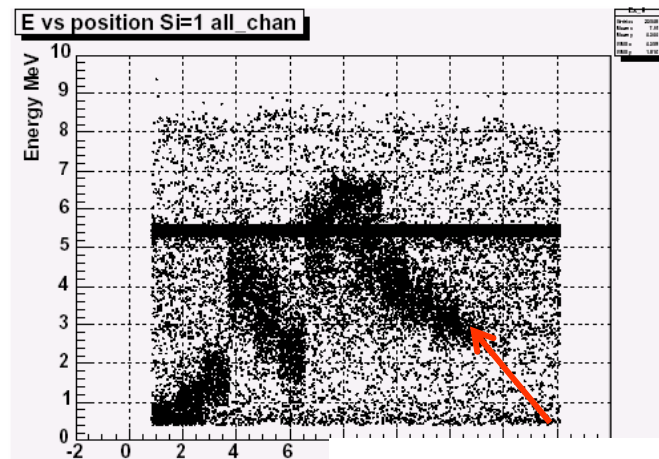Alessandro Bravar

Energy – Position correlations

$$T_{kin} \propto \theta^2 \text{ (i.e. position}^2)$$

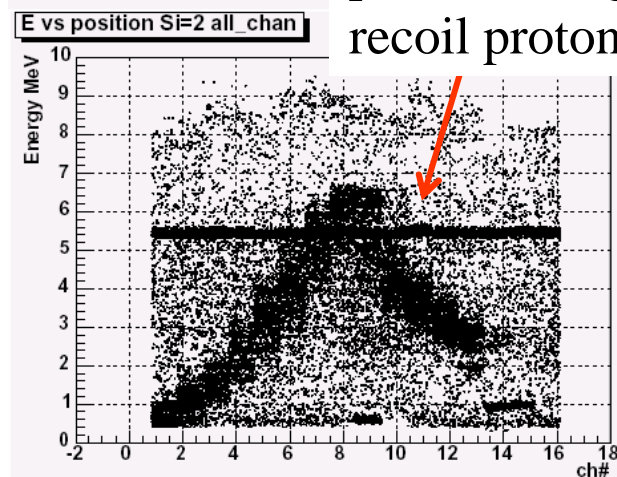fully absorbed protons

punch through protons

TDC vs ADC individual channels

recoil energy

punch through recoil protons

position

pp elastic events clearly identified !

Alessandro Bravar

BNL NATIONAL LABORATORY

Missing Mass M_X^2 @ 100 GeV

M_p^2

not corrected for the magnetic field

FWHM ~ 0.1 GeV^2

inelastic threshold

number of events (a. u.)

M_X^2 [GeV^2]

simulations

M_X^2 distribution 80 cm from target convoluted with spectrometer Resolution

ΔM_X^2 ~ 0.1 GeV^2

ΔM_X^2

proton

M_X^2 (GeV^2)

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

A_N for $p\!\uparrow\! p \rightarrow pp$ @ 100 GeV

statistical errors only

preliminary
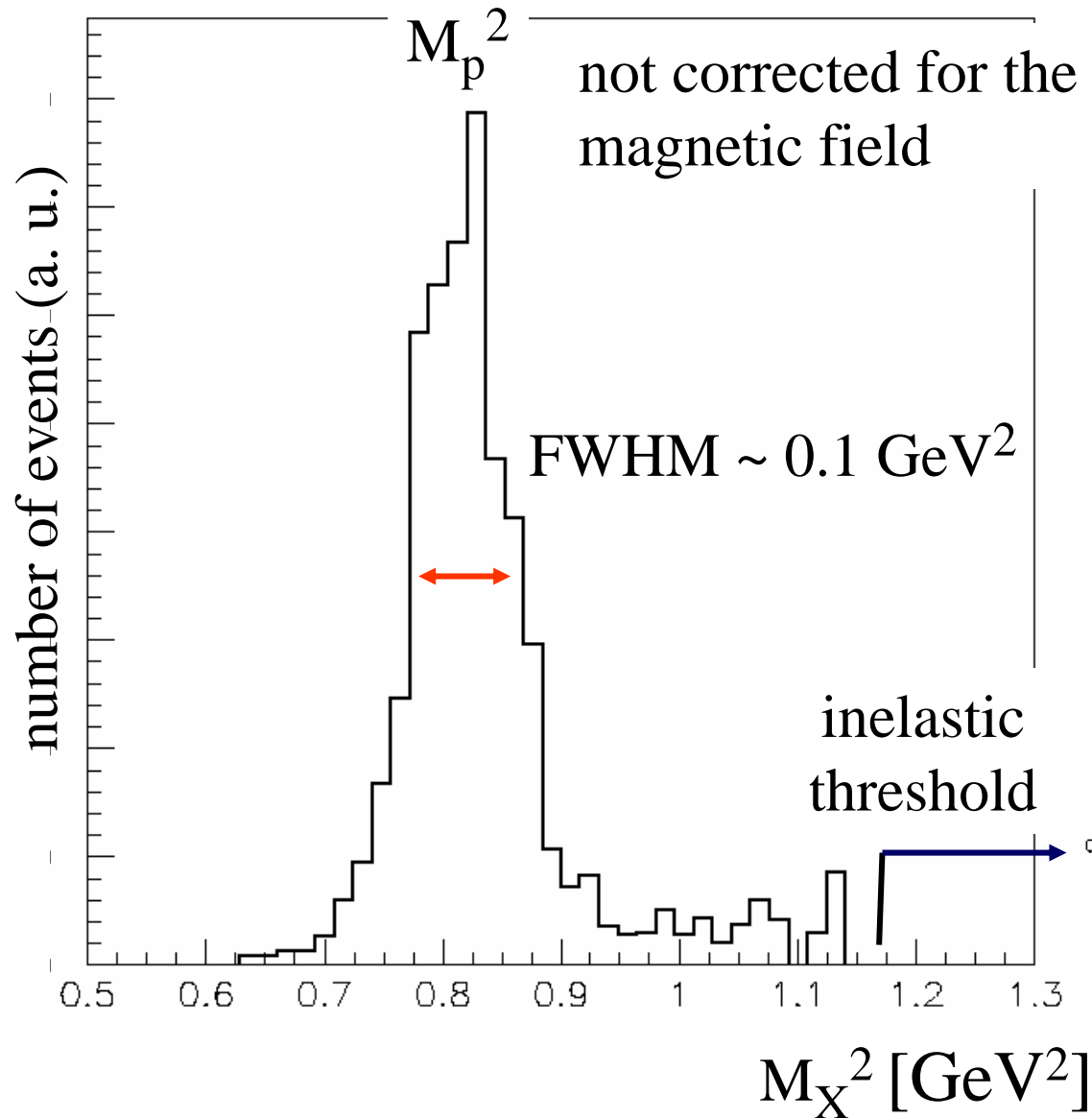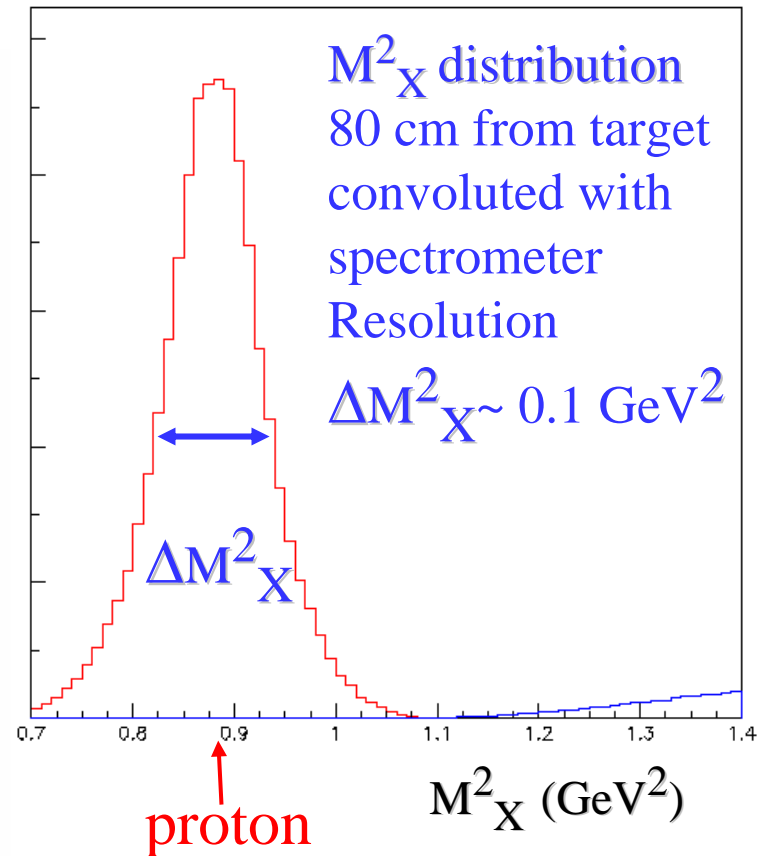
systematical error
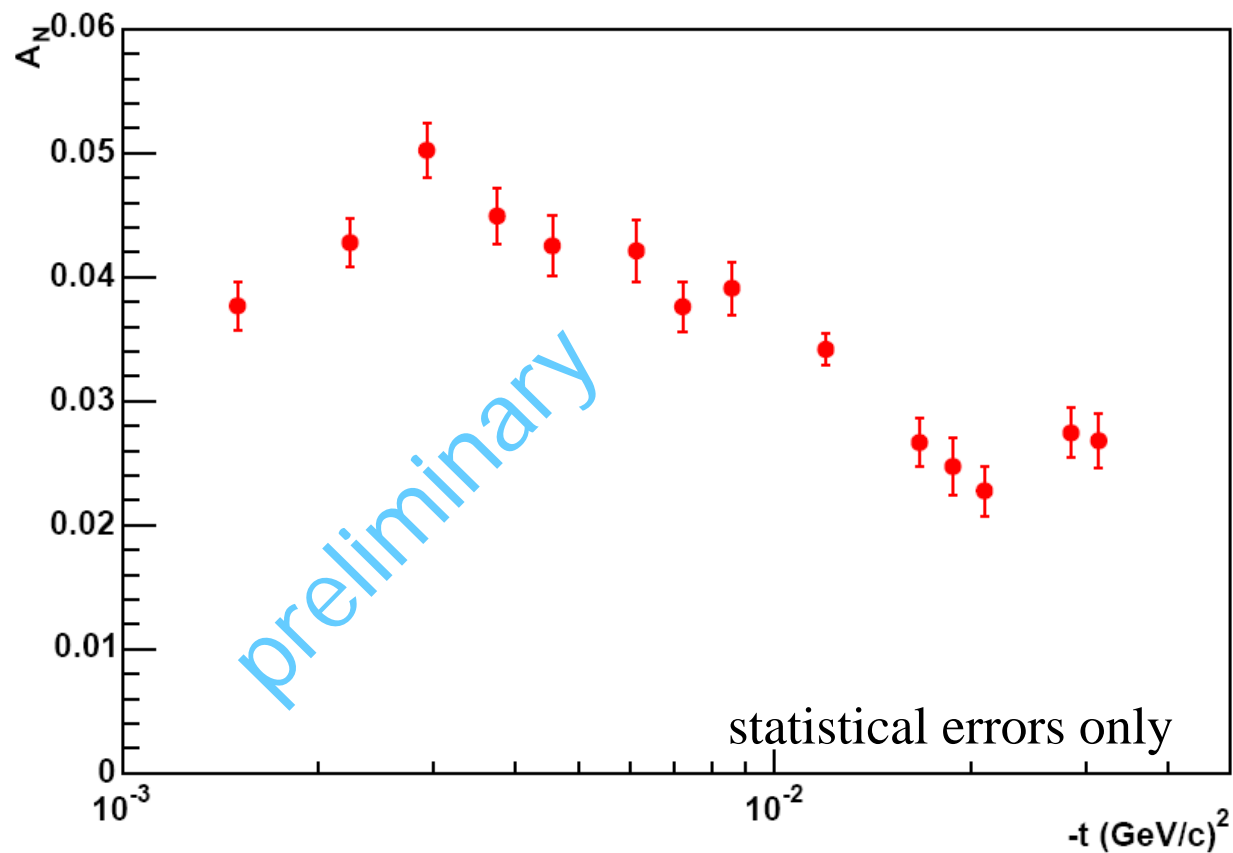
source of systematic errors:
1 $\Delta P_{TARGET} = 2\ \%$
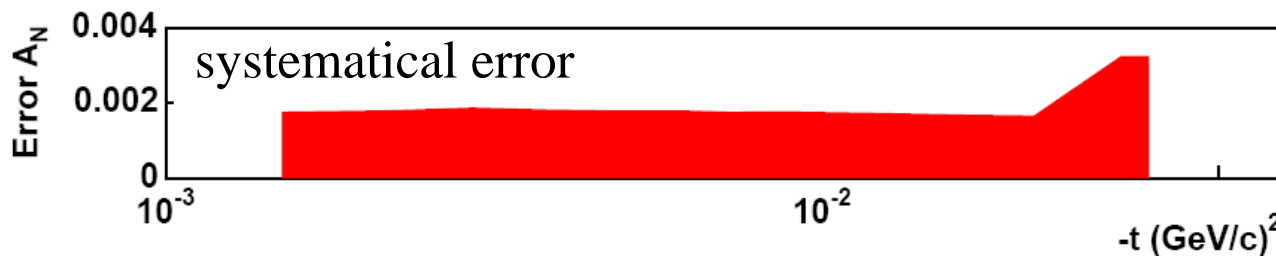2 from backgrounds
        $< \pm\ 0.0016$
3 false asymmetries: small

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

A_N for $p\uparrow p \rightarrow pp$ @ 100 GeV

- ● this exp
- ■ E704 @ FNAL

preliminary

no hadronic
spin-flip
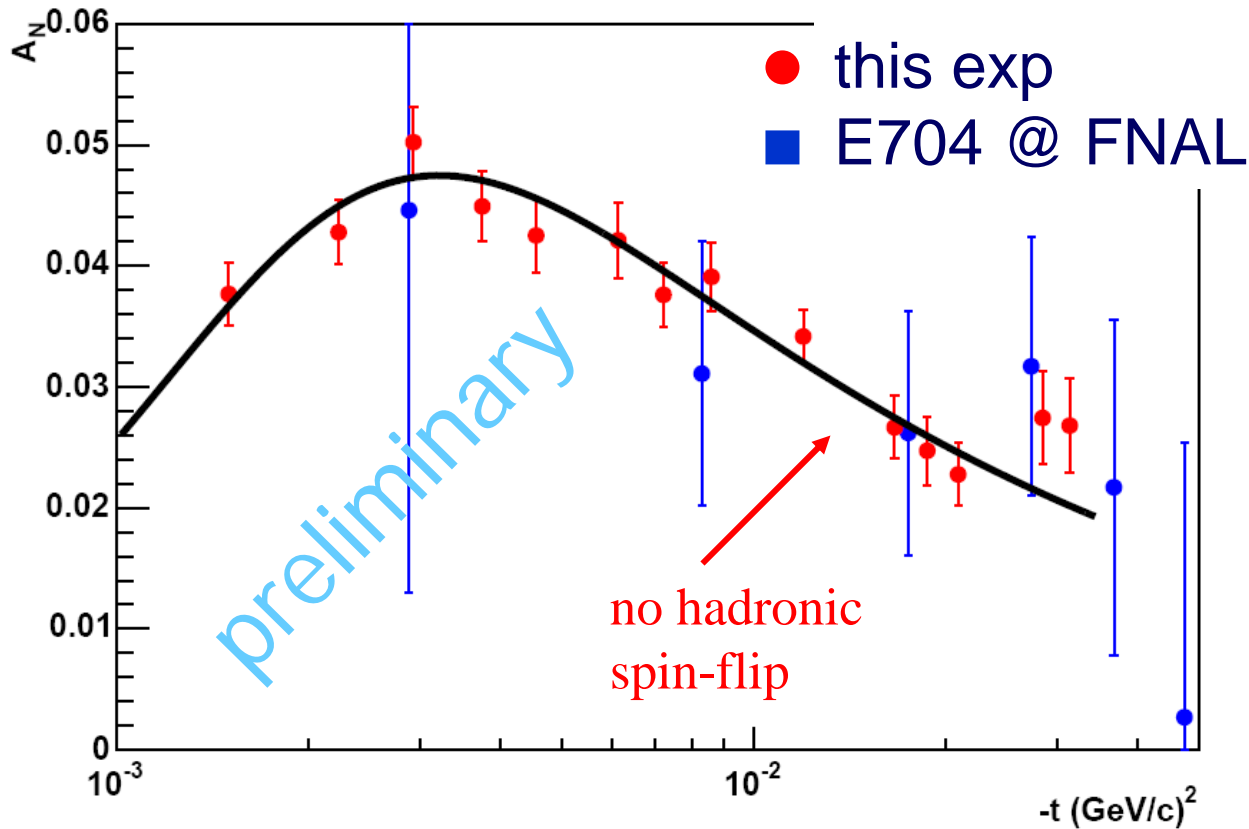
data (from this expt. only)
fitted with CNI prediction
[$\sigma_{TOT} = 38.5$ mbarn,
  $\rho = 0$, $\delta = 0$]

fitted with:
$\mathcal{N} \times f_{CNI}$
$\mathcal{N} -$
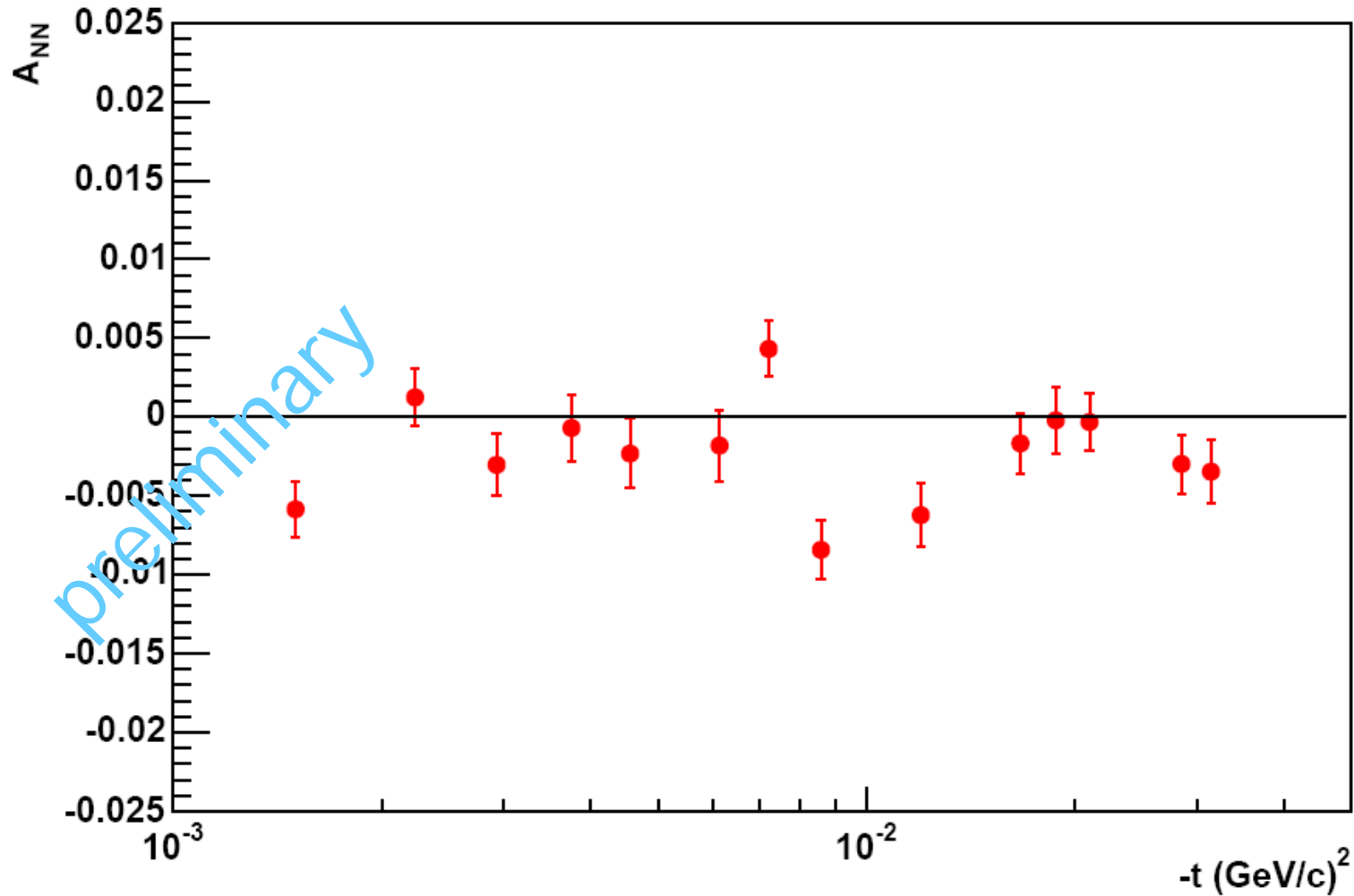 "normalization factor"
$\mathcal{N} = 1.01 \pm 0.02$
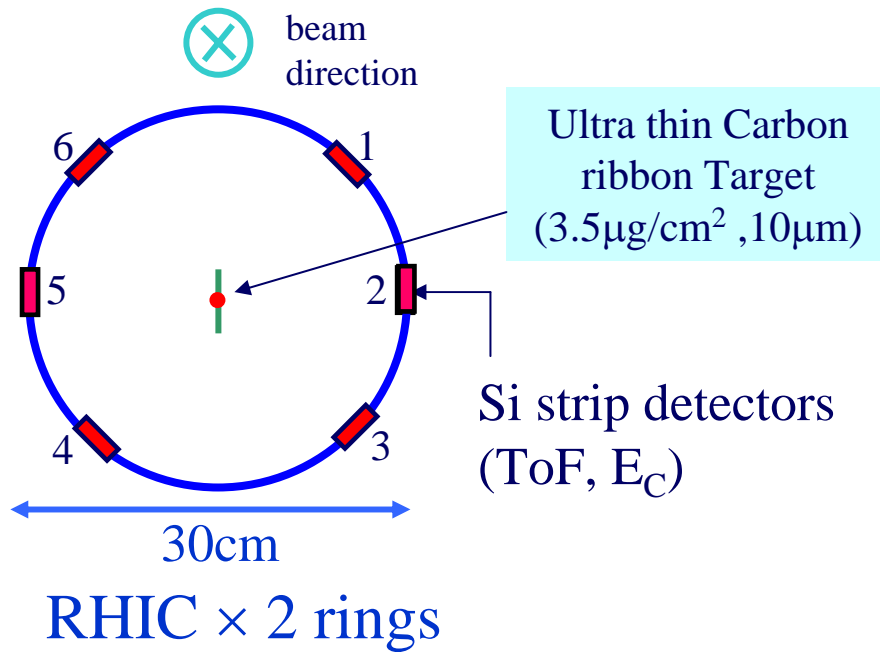$\chi^2 \sim 12 / 13$ d.o.f.

the errors shown are
statistical only
(see previous slide)

no need of a hadronic spin – flip contribution to describe these data
however, sensitivity on ϕ_5^{had} in this *t* range low

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

A_{NN} for $p\uparrow p\uparrow \rightarrow pp$ @ 100 GeV

To be completed . . . .

Alessandro Bravar

Setup for pC scattering – the RHIC polarimeters

beam direction

6 1

5 2

4 3

Ultra thin Carbon ribbon Target ($3.5\mu g/cm^2$, $10\mu m$)

Si strip detectors (ToF, E_C)
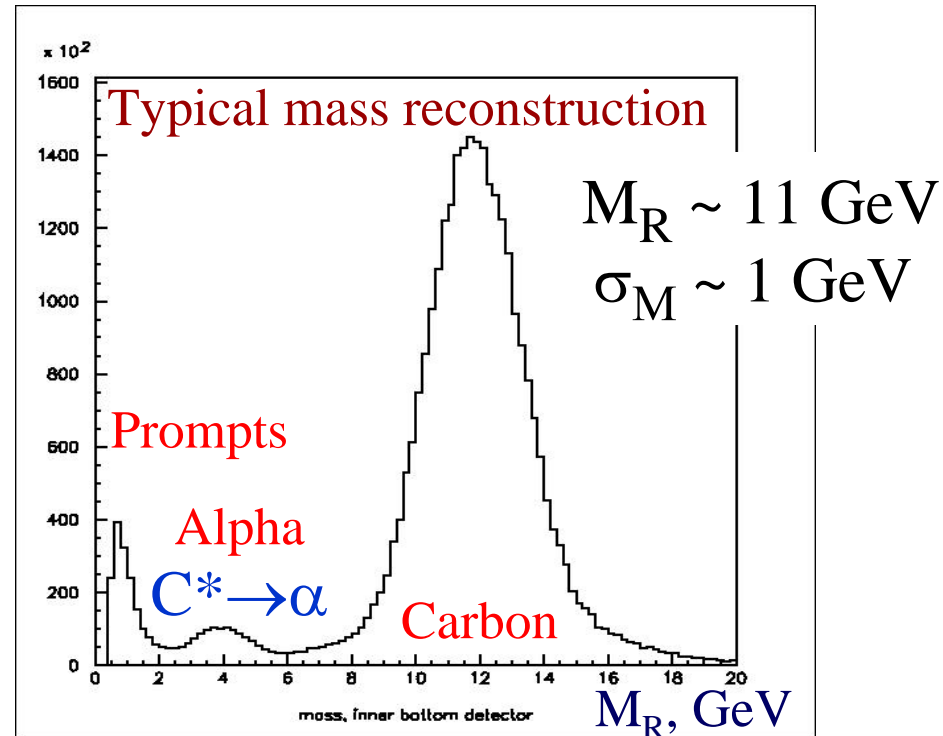
30cm

RHIC × 2 rings

inside RHIC ring @IP12
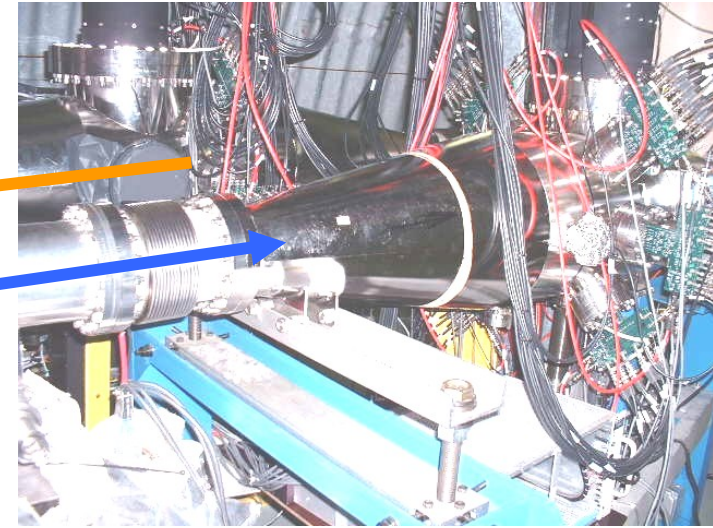
- recoil carbon ions detected with Silicon strip detectors
- 2×72 channels read out with WFD (increased acceptance by 2)
- very large statistics per measurement (~ 20×10^6 events) allows detailed analysis
  - bunch by bunch analysis
  - channel by channel (each channel is an "independent polarimeter")
  - 45° detectors: sensitive to vertical and radial components of $\vec{P}_{beam}$
    $\rightarrow$ unphysical asymmetries

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

Event Selection & Performance

TOF, ns

$T_{kin} = \frac{1}{2} M_R (dist/ToF)^2$

non-relativistic kinematics

Carbon

Alpha

Prompts

outer bottom detector

E_C, keV

Typical mass reconstruction

$M_R \sim 11$ GeV

$\sigma_M \sim 1$ GeV

Prompts

Alpha

$C^* \rightarrow \alpha$

Carbon

mass, inner bottom detector

M_R, GeV
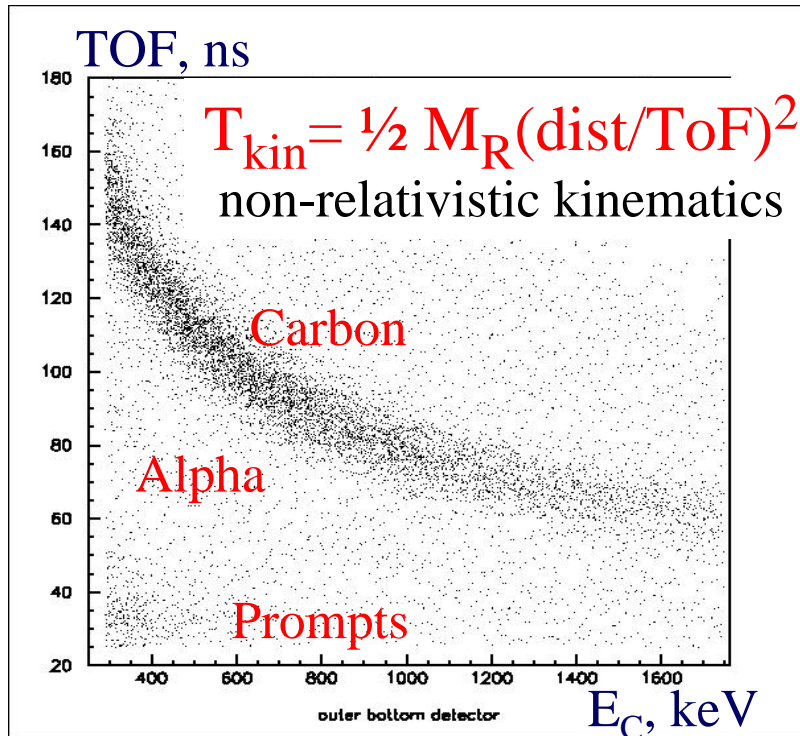
- very clean data, background < 1 % within "banana" cut

- good separation of recoil carbon from α ($C^* \rightarrow \alpha + X$) and prompts

  may allow going to very high $|t|$ values

- Δ (Tof) < ± 10 ns ($\Rightarrow \sigma_M \sim 1$ GeV)

- very high rate: 10^5 ev / ch / sec

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

A_N $p\!\uparrow\!C \rightarrow pC$ at 3.9, 6.5, 9.7 & 21.7 GeV (AGS)

momentum transfer $-t$ (GeV$^2/c^2$)

CNI peak ~ 4 %

preliminary
2003 + 2004 data

p = 3.9 GeV
$\langle P_B \rangle$ ~ 73 %

p = 6.5 GeV
$\langle P_B \rangle$ ~ 65 %

p = 9.7 GeV
$\langle P_B \rangle$ ~ 60 %

p = 21.7 GeV
$\langle P_B \rangle$ ~ 47 %

statistical errors only
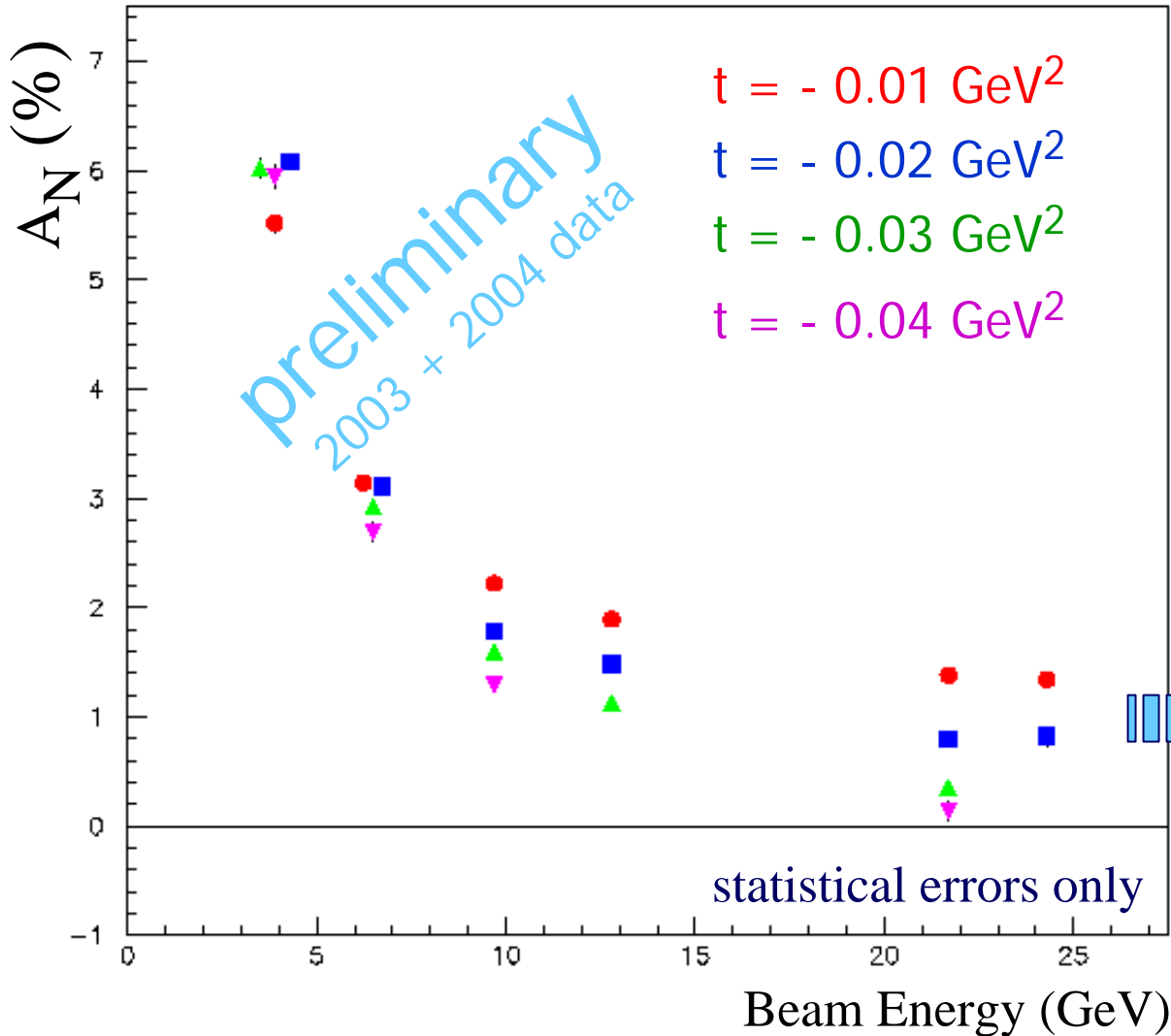
recoil Carbon energy (keV)
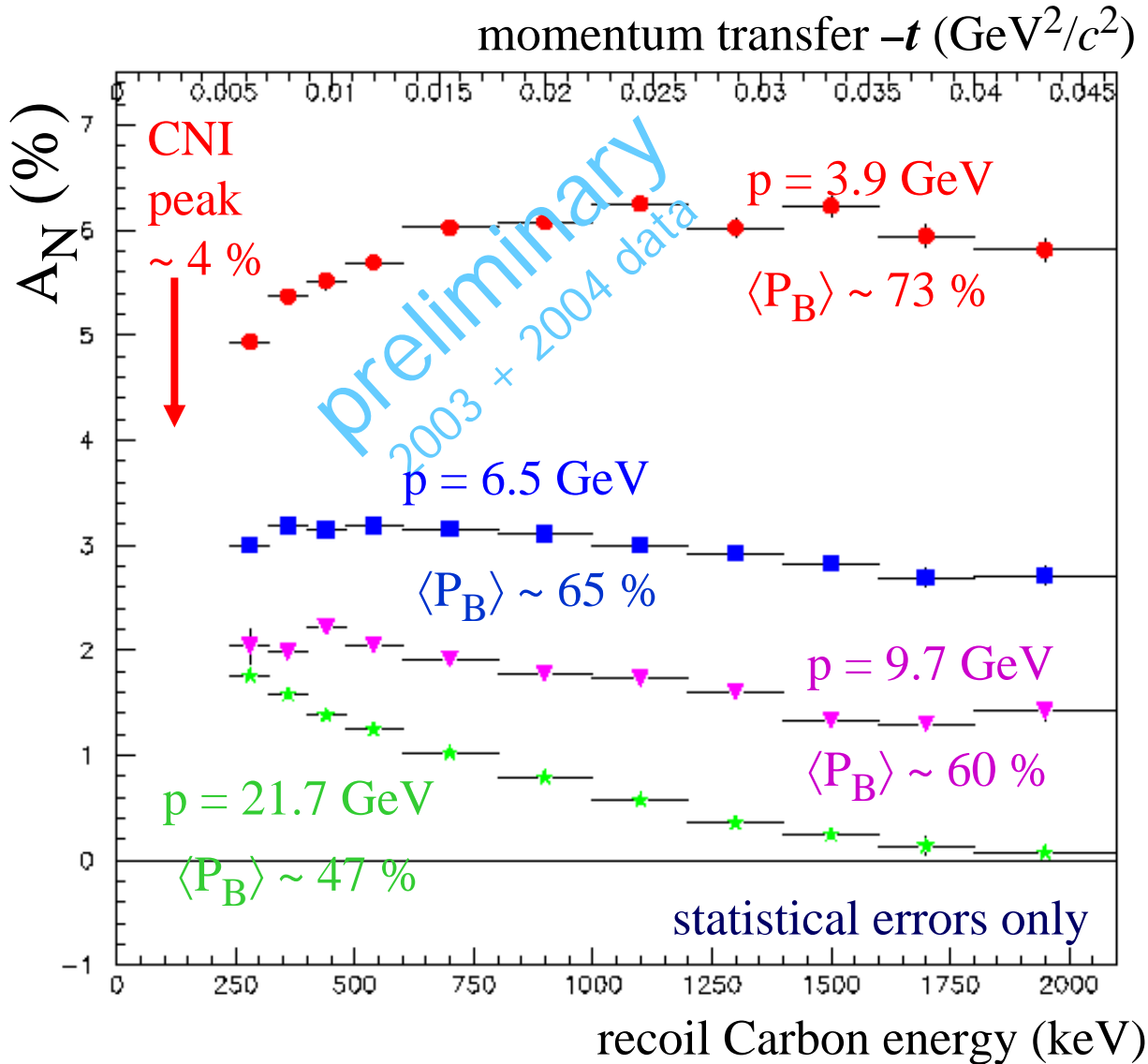
only statistical errors are shown

normalization errors:
~ 10 % (at 3.9)
~ 15 % (at 6.5)
~ 20 % (at 21.7)

systematic errors:
< 20 %
- backgrounds
- pileup
- RF noise

EDS05

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

A_N $p\uparrow C \to pC$: Energy Dependence

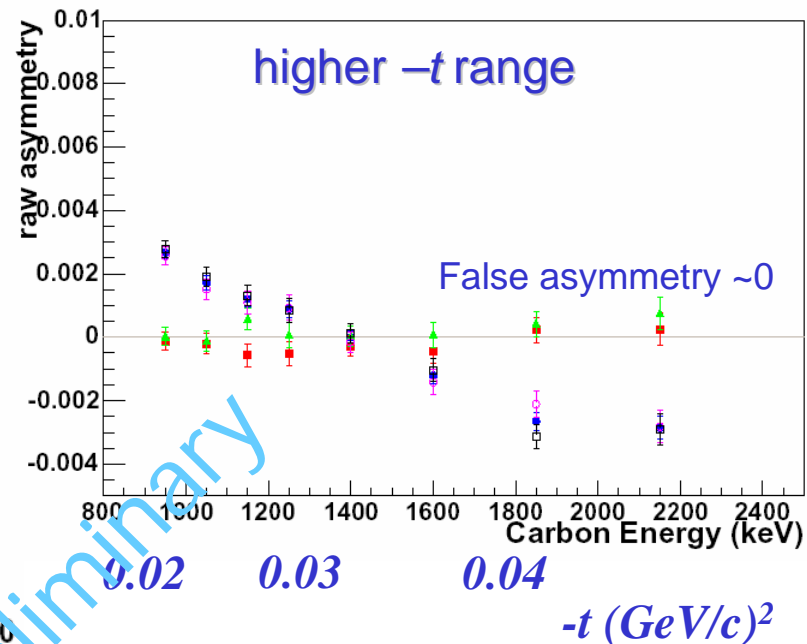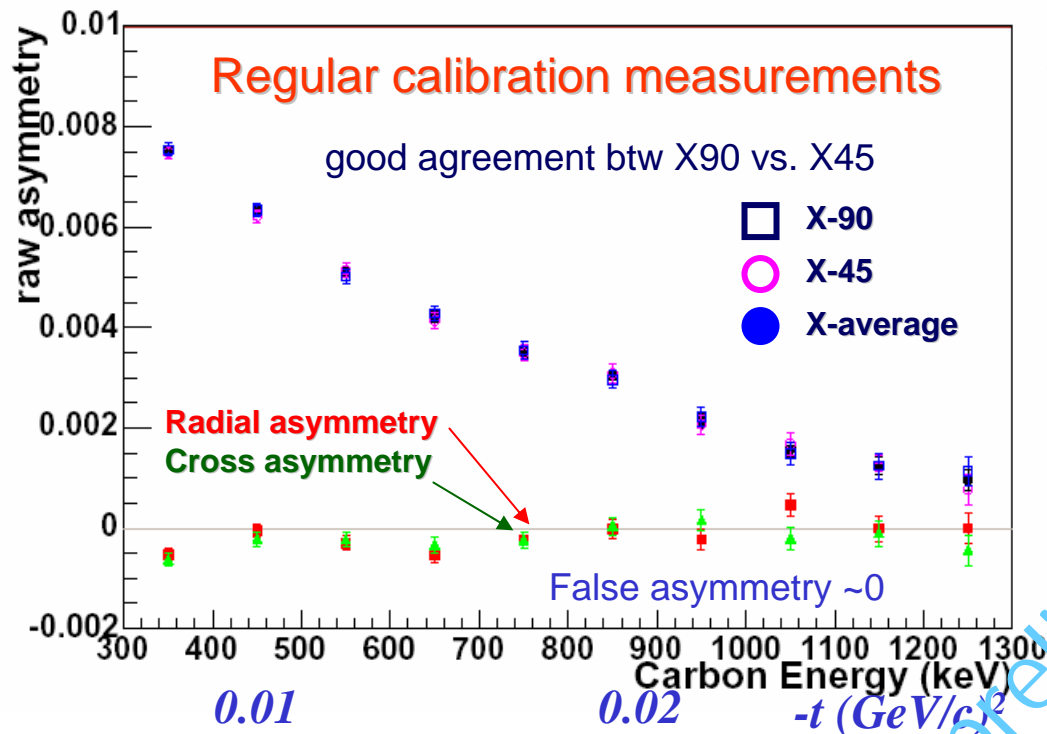only statistical errors
are shown
systematic errors
as for previous slide

Asymptotic regime

E ?

No energy dependence ?

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY

Raw asymmetry (*t*) @ 100 GeV (RHIC)
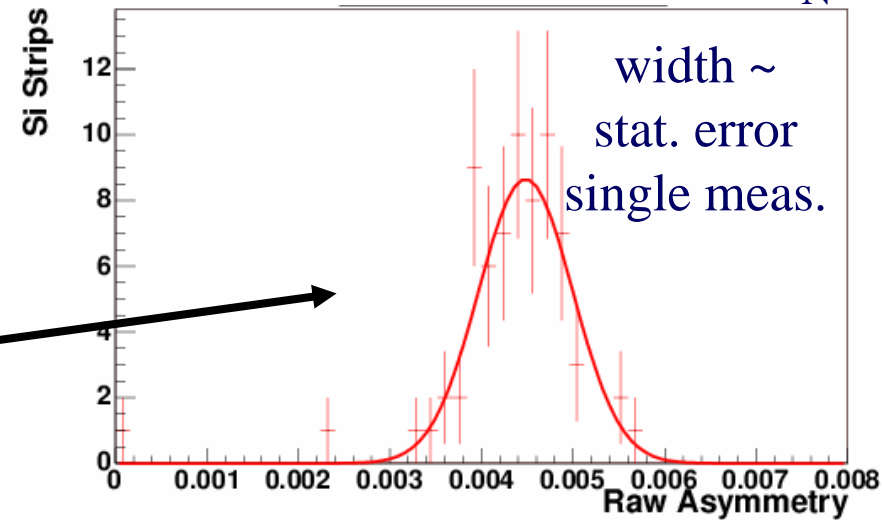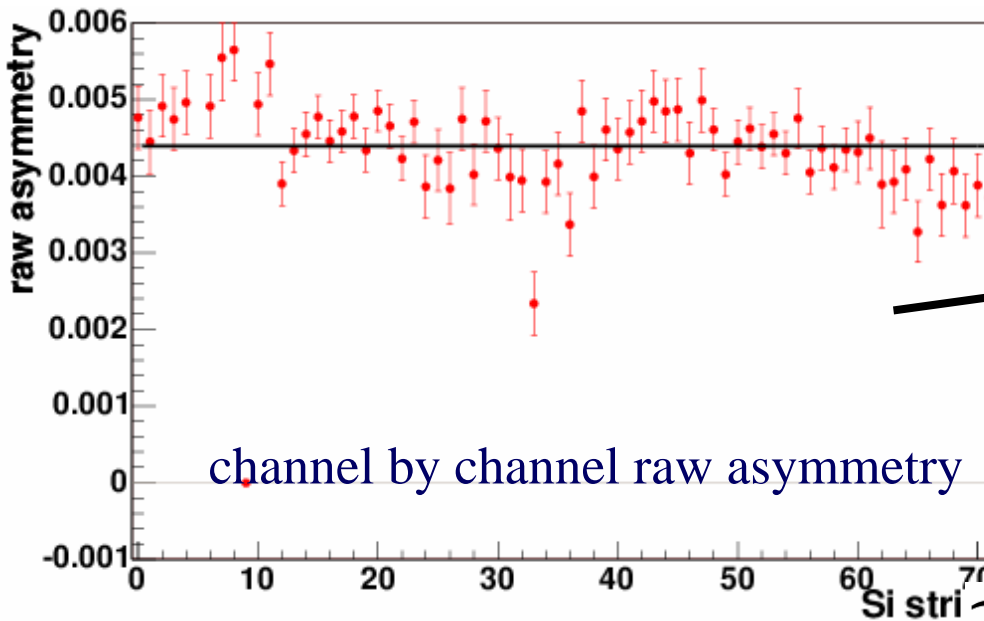

Regular polarimeter runs

measurements taken simultaneously with Jet -target

very stable behavior of measured asymmetries

Polarimeter dedicated runs (high -*t*)

Signal attenuation (x1/2) to reach higher –*t*

Normalized at overlap region to regular runs

Zero crossing measured with large significance

Alessandro Bravar

*p*C Systematics:

each detector channel covers same *t* range
→ 72 independent measurements of A_N

width ~
stat. error
single meas.

channel by channel raw asymmetry

Fit with sine function (phase fixed)
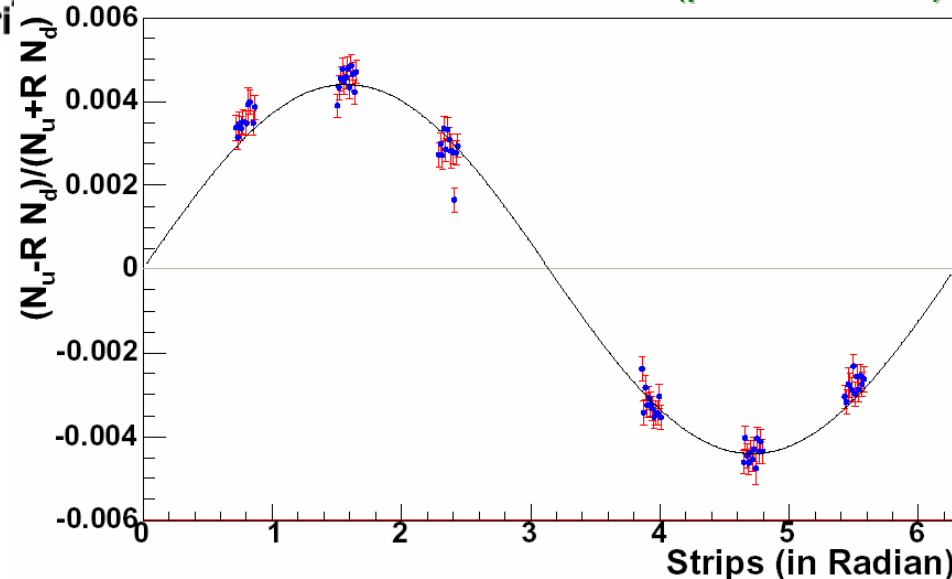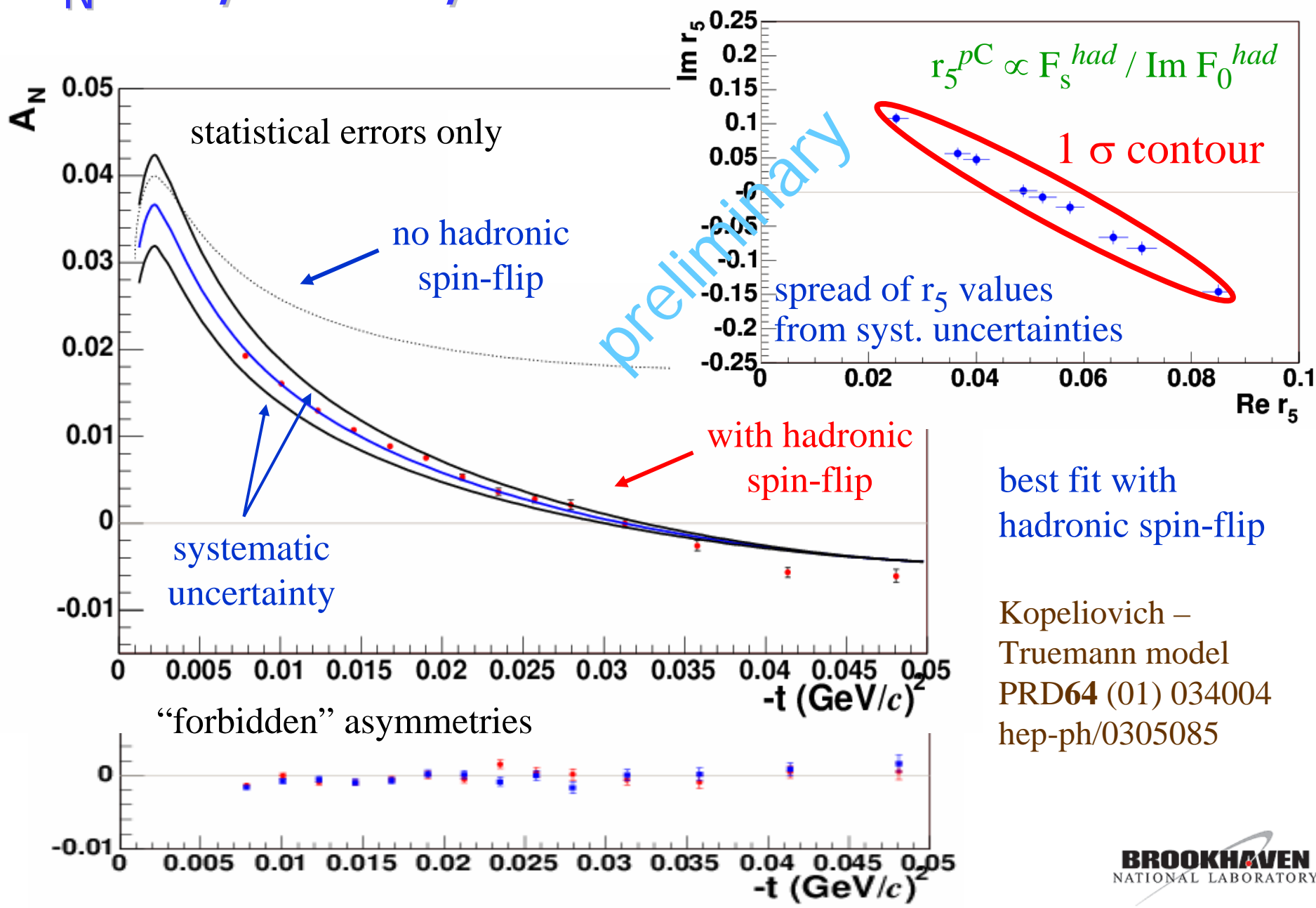

sources of systematic uncertainties:

1 ΔP_{BEAM} = 7.8 % (normalization)
[P_{BEAM} = 0.386 ± 0.030, stat. error]

2 energy scale ~ 50 keV for lowest |*t*| bin
(from detector dead layer)

NB   these are "external" factors
not "intrinsic" limitations

Alessandro Bravar

NATIONAL LABORATORY

A_N for $p\uparrow C \rightarrow pC$ @ 100 GeV

statistical errors only

no hadronic spin-flip

systematic uncertainty

with hadronic spin-flip

"forbidden" asymmetries

$r_5^{pC} \propto F_s^{had} / Im\ F_0^{had}$

preliminary

1 σ contour

spread of r_5 values from syst. uncertainties

best fit with hadronic spin-flip

Kopeliovich – Truemann model PRD**64** (01) 034004 hep-ph/0305085

BROOKHAVEN
NATIONAL LABORATORY

Summary

- measured A_N^{pp} and A_{NN}^{pp} for elastic $pp \rightarrow pp$ scattering at 100 GeV with very high accuracy (statistical and systematic)
  - $|t|$ range: $0.0015 < |t| < 0.035$ $(\mathrm{GeV}/c)^2$

- pp data well described by CNI – QED predictions ("S – LK")
  no need for a hadronic spin-flip term
  $A_{NN} \sim 0$ over whole measured range with no structure (t – dependence)

- measured A_N^{pC} for elastic pC $\rightarrow$ pC scattering at 100 GeV (RHIC)
  - zero crossing around $|t| \sim 0.03$ $(\mathrm{GeV/c})^2$

- pC data require substantial hadronic spin-flip !

- measured A_N^{pC} for pC $\rightarrow$ pC scattering over $3.5 < E_b < 24$ GeV (AGS)
  - $E_b < 10$ GeV/c: almost no t dependence & departure from "CNI" shape

Alessandro Bravar

BROOKHAVEN
NATIONAL LABORATORY